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REVIEW PAPER

Bioaerosols in the landfill environment: an overview of microbial diversity and potential health hazards

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Abstract Landfilling is one of the indispensable parts of solid waste management in various countries. Solid waste disposed of in landfill sites provides nutrients for the proliferation of pathogenic microbes which are aerosolized into the atmosphere due to the local meteorology and various waste disposal activities. Bioaerosols released from landfill sites can create health issues for employees and adjoining public. The present study offers an overview of the microbial diversity reported in the air samples collected from various landfill sites worldwide. This paper also discusses other aspects, including effect of meteorological conditions on the bioaerosol concentrations, sampling techniques, bioaerosol exposure and potential health impacts. Analysis of literature concluded that landfill air is dominated by microbial dust or various pathogenic microbes like *Enterobacteriaceae*, *Staphylococcus aureus*, *Clostridium perfringens*, *Acinetobacter calcoaceticus* and *Aspergillus fumigatus*. The bioaerosols present in the landfill environment are of respirable sizes and can penetrate deep into lower respiratory systems and trigger respiratory symptoms and chronic pulmonary diseases. Most studies reported higher bioaerosol concentrations in spring and summer as higher temperature and relative humidity provide a favourable environment for survival and multiplication of microbes. Landfill workers involved in solid waste disposal activities are at the highest risk of exposure to these bioaerosols due to their proximity to solid waste and as they practise minimum personal safety and hygiene measures during working hours. Workers are recommended to use personal protective equipment and practise hygiene to reduce the impact of occupational exposure to bioaerosols.

Keywords Bioaerosols · Air pollutants · Organic dust · Occupational health · Landfill site · Aerobiological monitoring

Abbreviations

CFU	Colony-forming unit
GNB	Gram-negative bacteria
MSW	Municipal solid waste
ODTS	Organic dust toxic syndrome
PPE	Personal protective equipment
RH	Relative humidity
TVB	Total viable bacteria
US EPA	United States Environmental Protection Agency

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1 Introduction

Bioaerosols omnipresent in the atmosphere, are incredibly variable and complex and perform important roles in almost all ecological units (Ghosh et al. 2015). Bioaerosols are airborne biological particles consisting of cells, pollen, fungi, parasite eggs, bacteria or viruses (Blais-Lecours et al. 2015; Breza-Boruta 2016; Douglas et al. 2017). To a great extent, these airborne microbes are present in the atmosphere due to natural origin like the forest, marine environment and desert dust. The components of bioaerosols studied by aerobiologists include (1) living organisms—including fungi, bacteria, microalgae, lichens; (2) biological components—including spores, pollen, viruses, mycotoxins, endotoxins, exotoxins, proteins, (1-3)-β-D-glucans, and (3) non-biological particles, organic dust, animal fragments/excreta (Pearson et al. 2015; Rengasamy et al. 2004; Šantl-Temkiv et al. 2020). Bioaerosols have a biogeochemical association with atmospheric, marine and terrestrial environment and play a critical role in ecosystem interaction, nucleation and human health (Walser et al. 2015; Zhai et al. 2018).

Bioaerosols exhibit high variability in shape and sizes. The size of pollen grains varies between 5 and 300 µm, while fungal cells and spores varies from 0.25 to 60 µm and the size of viruses are mostly less than 0.2 µm (Sturm 2012). Fragments of cells and colonies vary from some nanometres to hundreds of micrometre (Sturm 2012). The age of spores governs the bioaerosol size variation, types of associated particles, type of microbes and aggregation rates of microbes (Chmiel and Kral 2019). Irrespective of the diverse compositions, shape, size structures and category, most bioaerosols have an aerodynamic diameter less than 10 µm and can penetrate deep inside the respiratory tract (Sharma Ghimire et al. 2019). Bioaerosols entering the respiratory tracks and deep into lungs and to the alveolar, sac induce numerous adverse health effects, including allergies, pneumonia, rhinitis, hay fever, asthma, tuberculosis, bronchitis and cardiovascular diseases (Breza-Boruta 2016; Douglas et al. 2017). Additionally, bioaerosols encompassing non-culturable microbes or their fragments are also responsible for chronic diseases (Blais-Lecours et al. 2015).

Biological processes in waste industries like wastewater treatment, solid waste composting and landfilling house many pathogenic bioaerosols at the workplace (Pasmionka 2020; Yoo et al. 2016). In waste treatment plants, complex biological and physicochemical processes are used in a controlled environment to treat waste materials, leading to the release many pathogenic bioaerosols into the atmosphere (Walser et al. 2015; Wolany and Płaza 2017). Wastewater treatment plants contain several pathogenic microbes, including the new novel coronavirus SARS-CoV-2 (Burdsall et al. 2020). A recent study has reported forty-one antibiotic-resistant bacteria present downwind of MSW treatment plant (Li et al. 2020). Several researchers have confirmed that occupational exposure to bioaerosols at workplaces like composting, wastewater treatment plant, landfills can cause various allergic, inflammatory and infectious diseases (Pasmionka 2020; Ray et al. 2005; Walser et al. 2015).

Solid waste management is considered to be one of the most critical indicators of good city governance. By 2025, the urban population worldwide is anticipated to reach around 4.3 billion, generating around 2.2 billion tonnes of MSW every year (The World Bank 2012). In most countries, the final accountability of solid waste management lies with the municipalities/ urban local bodies. However, a large portion of the population does not receive adequate MSW management services (Paul et al. 2012). Though being the least favourable method in the MSW management hierarchy, in most developing countries, due to scarcity of financial support, technical expertise and institutional efforts, unscientific open dumping of MSW in unlined open dumps is preferred for MSW disposal (Nair et al. 2019a; Samadder et al. 2017). Such landfills release a large amount of organic dust, VOCs, leachate and bioaerosols (Kalwasińska and Burkowska 2013; Madhwal et al. 2020; Nair et al. 2019a, b). Most landfill sites provide favourable conditions such as nutrients and moisture for degradation of waste and proliferation of microbes, some of which are pathogenic. Exposure to these bioaerosols from landfill sites could lead to irritations of the eye and skin, and increased risk of gastrointestinal symptoms (Ray et al. 2005).

The microbes proliferate abundantly on the nutrients present in the biodegradable MSW, which forms the significant stake of the waste disposed of in landfills (Madhwal et al. 2020). These microbes along with dust particles are aerosolized during various waste management activities comprising transporting the waste to landfill sites, unloading the waste from the vehicles, spreading and levelling, sorting, compacting and covering the waste with soil (Kalwasińska et al. 2014). The dust particles can comprise pathogenic microbes, cytotoxins and endotoxins (Maharia and Srivastava 2020; Schlosser et al. 2018). The increasing population of cities in developing countries and expanding periphery of the urban area has brought landfill sites nearby or within the city border. Therefore, people are destined to reside adjacent to landfill sites, a potential source of bioaerosol-related epidemic disease outbreak (Madhwal et al. 2020). The concentrations of bioaerosols in a landfill site can be a thousand times greater than in any office building (Kalwasińska et al. 2014; Lis et al. 2004).

Landfilling operations in most developed countries are mechanized, and workers practise adequate personal safety measures and wear PPE; however, in developing countries, landfill workers handle the waste with bare minimum personal protective equipment and personal hygiene (Salve et al. 2019). Major waste handling activities like waste collection, transportation, unloading of waste, sorting and final disposal are carried out by workers physically with minimum mechanization and personal protection. They physically handle various toxic waste like decaying waste, carcasses of animals, excreta of human and animals which puts them at risk of communicable and non-communicable diseases (Salve et al. 2019). Hence, the workforces of landfill sites in developing countries are most exposed to organic dust and dangerous bioaerosol and put them at high risk of occupational hazards. The primary exposure routes of bioaerosols are through inhalation and dermal contact (Ray et al. 2005). Apart from formal landfill workers, another group of people exposed to such high concentrations of bioaerosols are residents near landfill sites and informal waste pickers or scavengers in the dumpsite. Informal waste pickers spend the maximum amount of time in the landfill site with minimum personal protection and hygiene (Fig. 1). Hence, it is imperative to consider the microbiological air quality of landfill and surrounding area to develop suitable safety interventions. This paper aims to provide an overview of published literature highlighting the various species and concentrations of bioaerosols collected and identified from landfill air across the world, their seasonal analysis and associated exposure hazards. Bioaerosol sampling methods, along with their benefits and limitations, are also discussed.

2 Microbial diversity in landfill sites

Knowledge of microbial diversity present in the landfill and the surrounding atmosphere is essential to avert its harmful health hazards. The type and quantity of pathogenic bioaerosols in landfill air are influenced by various factors like composition of waste, nature of microbes present in the landfill site, bio-meteorological conditions like wind speed, wind directions, temperature, atmospheric pressure, humidity, precipitation, solar radiation and electric phenomena (Kalwasińska and Burkowska 2013; Krishnamurthi and Chakrabarti 2013). Hence, the quantity and composition of the microbial diversity always exhibit inconsistency and therefore cannot be reported with certainty. A varied array of microorganisms exist in landfill sites as they play significant roles in the degradation of organic waste disposed in landfills over time (Awasthi et al. 2017; Krishnamurthi and Chakrabarti 2013). Microbes degrade the organic compounds present in MSW in methane, carbon dioxide, water vapour and VOCs (Nair et al. 2019a). The most common microbial group detected in landfills are cellulose degraders, acidogens, acetogens and methanogens (Xu et al. 2017). Some of the bacteria like *Escherichia coli, Proteus mirabilis, Staphylococcus sciurii, Staphylococcus xylosus* and fungi like *Aspergillus fumigatus, Aspergillus flavus* are responsible for the degradation of waste disposed of in landfill (Fraczek and Kozdroj 2016). However, these microbes are also associated with various infections in human beings, specifically in the respiratory system (Fraczek and Kozdroj 2016; O'Gorman 2011). These microbes can be disseminated from landfill sites mainly via three modes–leachate, vector and aerosols (Fedorak and Rogers 1991). Krishnamurthi and Chakrabarti (2013) reported the presence of *Actinobacteria, Aerococcus, Bacillus, Brevibacillus, Clostridium, Cohnella, Desulfotomaculum, Lysinibacillus, Microvirga, Oceanobacillus, Ornithinibacillus, Paenibacillus, Paenisporosarcina, Pseudomonas, Roseomonas, Staphylococcus, Stenotrophomonas* and *Streptococcus* in landfill situated in India. Figure 2 shows the microbial diversity analysed

Fig. 1 Informal waste pickers handling solid waste in an open dumpsite without any personal protection (*Source*: Author's own)

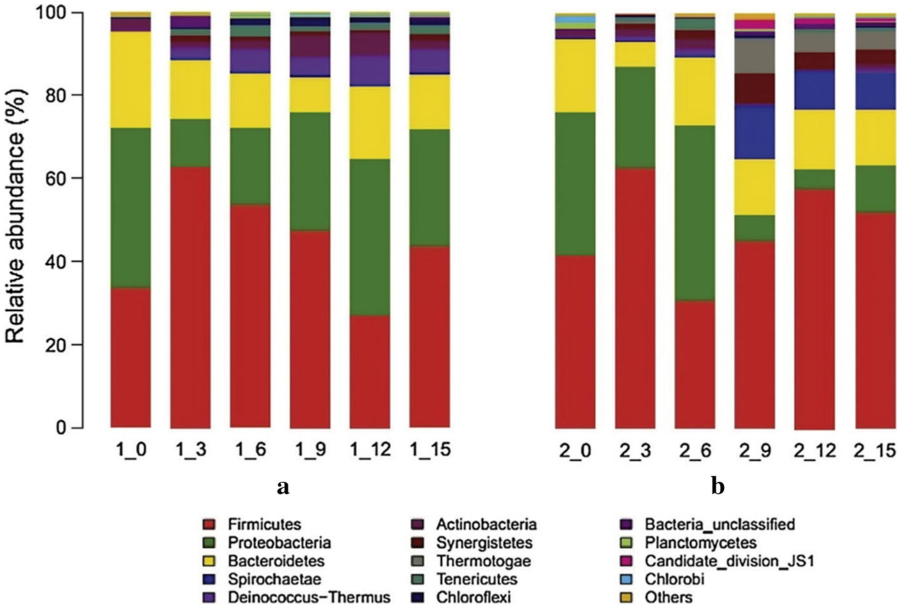

Fig. 2 Microbial diversity present at two sampling locations in Zhaozhuang landfill, China [Reproduced with permission from Wang et al. (2017)]

from Zhaozhuang landfill, China. The results reveal the presence of *Actinobacteria, Bacteroidetes, Firmicutes, Deinococcus-Thermus, Proteobacteria, Spirochaetes, Synergistetes, Thermotogae* and *Tenericutes* (Wang et al. 2017).

The primary source of bioaerosols in the landfill site is the deposited organic waste. Some elements of MSW disposed of in landfills may comprise enteric pathogenic microorganisms. MSW discarded from residential units contains decomposed raw and cooked food waste, faecal matter of pets, soiled diapers and facial tissues which house a large quantity of microbes (Pahren and Clark 2009). Similarly, commercial units like restaurants and hotels discard a large amount of putrescible food waste. An exhaustive investigation carried out by the US EPA found that pet faeces contributed to 94–97% of *Salmonellae*, human enteroviruses and protozoan parasites, while waste food contributes to more than 80% enteric bacterial pathogens in landfill (Gerba et al. 2011). Poliovirus 3, echovirus 2, noroviruses and *Cryptosporidium* were reportedly recovered from soiled diapers disposed of in landfill sites (Gerba et al. 2011; Peterson 1974). Analysis of air samples collected from some landfills has also reported the presence of human adenovirus (Carducci et al. 2013). Apart from MSW deposited, the soil used to cover the MSW disposed of can also contain a high amount of microbes (Kalwasińska and Burkowska 2013). However, MSW disposed of in landfill has a significantly higher diversity of microbial diversity than cover soil (Wang et al. 2017).

The bioaerosols released from the landfill sites commonly comprise bacterial species including *Bacillus, Clavibacter, Corynebacterium, Curtobacterium, Micrococcus, Pseudomonas and Staphylococcus*, while fungal types include *Cladosporium Alternaria*, *Penicillium* and *Aspergillus* (Abdel Hameed et al. 2015; Kaarakainen et al. 2008; Kalwasińska et al. 2014; Kalwasińska and Burkowska 2013; Pagalilauan et al. 2018; Schlosser et al. 2016; Vilavert et al. 2012). The most abundant phyla present in landfill includes *Firmicutes* followed by *Actinobacteria* and *Proteobacteria* (Krishnamurthi and Chakrabarti 2013; Xu et al. 2017). Several *Firmicutes* produce endospores, like *Bacillus* and *Clostridium,* which can survive extreme conditions (Zhang et al. 2016). Rahkonen et al. (1990) studied the concentrations of microbes from two sanitary landfills in Finland and found that mesophilic bacteria and mesophilic fungi exceeded 10^5 CFU m^{-3} and 10^4 CFU m^{-3}, respectively. 40% of the bacteria and 80% of fungi present in the landfill working environment were of respirable size. The most abundant bacteria detected in the landfill environment were *Pseudomonas*, *Enterobacter* and *Bacillus* spp. (Rahkonen et al. 1990). Huang et al. (2002) reported the presence of *Acremonium, Alternaria, Aspergillus, Cladosporium, Curvularia, Drechslera, Microsporum nanum, Nigrospora, Paecilomyces, Rhinocladiella, Stachybotrys, Tritirachium, Zygosporium*, zygomycetes and yeast from air samples of landfill sites in southern Taiwan. Kalwasińska et al. (2014) studied the microbial air quality of outdoor (operating landfill cell, technological square) and indoor space (sorting station, weighing station, social room) of the landfill site in Poland. The bioaerosol released in MSW facility consisted of bacterial species like *Bacillus subtilis, Pseudomonas aeruginosa* and fungal species like *Scedosporium apiospermum, Aspergillus fumigatus, Cryptococcus neoformans, Madurella grisea and Penicillium marneffei.* Pagalilauan et al. (2017) reported the presence of *Staphylococcus aureus*, *Staphylococcus hominis, Staphylococcus kloosii* and *Staphylococcus arlettae* in the air samples of landfill site situated in the Philippines. Further details of the bioaerosols reported from various landfill sites are presented in Table 1.

3 Spatial variations in bioaerosol concentrations

The concentration of bioaerosols in various landfill sections depends on meteorological conditions, on the distance from operational areas and waste management activities (Breza-Boruta 2016). The maximum quantity of potential pathogenic bioaerosols was reported in the main operational area of the landfill site (Kalwasińska and Burkowska 2013; Pagalilauan et al. 2018). High traffic of vehicles carrying waste, waste unloading and levelling operation aerosolize the microbes present in the solid waste resulting in high concentrations of bioaerosols (Breza-Boruta 2012). The concentrations of bioaerosols decrease with the distance from the landfill sites (Vilavert et al. 2012). The decrease in the bioaerosol concentration is higher in downwind compared to upwind (Kalwasińska and Burkowska 2013). The spores and conidia of the microbes can remain airborne for a long time and can be transported to long distances (Blais-Lecours et al. 2015; O'Gorman 2011).

Kalwasińska and Burkowska (2013) analysed the bioaerosols in the air samples of the landfill site in Toruń, Poland. Air samples were collected from

Table 1 Concentrations of bioaerosols and the corresponding species studies in different landfills across the world

Continents	Landfill location	Concentration	Bioaerosol species studied	References
Asia	Taiwan	Fungi 1.1×10^{4} CFU m^{-3} (mean)	*Cladosporium*, *Penicillium*, *Aspergillus*, *Drechslera*, *Alternaria*, *Fusarium*, *Acremonium*, *Tritirachium*, non-sporing fungi and yeast	Huang et al. (2002)
	Payatas, the Philippines	Bacteria 7.87×10^{2} to 5.57×10^{3} CFU m^{-3}	*Bacillus subtilis*, *Staphylococcus aureus*, *Klebsiella pneumonia*, *Staphylococcus saprophyticus*	Pagalilauan et al. (2018)
	Korea	Bacteria 8.5×10^{2} CFU m^{-3} (mean)	*Micrococcus*, *Aerococcus*, *Staphylococcus*, *Microbacterium and Bacillus*	Heo et al. (2010)
	Dehradun, India	Bacteria 3.6×10^{3} CFU m^{-3} (mean) Fungii 4.6×10^{3} CFU m^{-3} (mean)	*Aspergillus*, *Penicillium*, *Cladosporium*, *Alternaria; Bacillus*, *Streptobacillus*, *Coccus*	Madhwal et al. (2020)
	Mumbai, India	Fungi 6.20×10^{2} to 1.45×10^{3} CFU m^{-3}	*Aspergillus*, *Peniciliium*, *Alternaria*, *Curvularia*, *Trichoderma and Rhizopus*	Patil and Kakde (2017)
	Iran	Bacteria 8.9×10^{2} to 2.3×10^{3} CFU m^{-3} Fungi 4.1×10^{2} to 8.46×10^{2} CFU m^{-3}	*Staphylococcus*, *Bacillus cereus*, *Lactobacillus*, *Cladosporium*, *Aspergillus Alternaria*	Roodbari et al. (2013)
Africa	Giza, Egypt	Fungi 4.3×10^{2} to 7.3×10^{3} CFU m^{-3} Bacteria 0.0 to 7.3×10^{3} CFU m^{-3}	*Aspergillus terreus*, *Aspergillus ochraceus*, *Acremonium*, *Geotrichum*, *Aureobasidium*, *Sepedomium*, *Streptomyces diastaticus*, *Pseudonocardia compacta and Catellatospora ferruginea*	Abdel Hameed et al. (2015) Abdel Hameed and El Gendy (2014)
	Lagos, Nigeria	Bacteria 2.189×10^{3} CFU m^{-3} (mean) Fungi 8.43×10^{2} CFU m^{-3} (mean)	*Aspergillus fumigatus*	Akpeimeh et al. (2019)
	Ghana	Bacteria; 1.08×10^{2} CFU m^{-3} to 7.03×10^{2} CFU m^{-3} Fungi 1 CFU m^{-3} to 2.0×10^{2} CFU m^{-3}	*Staphylococcus epidermidis*, *Staphylococcus aureus*, *Pseudomonas aeruginosa*, *Escherichia coli*, *Aspergillus flavus*, *Aspergillus niger*	Odonkor and Mahami (2020)

Table 1 continued

Continents	Landfill location	Concentration	Bioaerosol species studied	References
Europe	Sosnowiec, Poland	Bacteria 7.2×10^4 CFU m^{-3} Fungii 1.2×10^4 CFU m^{-3}	*Acinetobacter lwoffi*, *Rhodococcus* spp., *Corynebacterium afermentas and Corynebacterium aquaticum;*Propagules of *Cladosporium herbarum*, pink and white yeasts, *Arthrographis alba*, *Geotrichum candidum*, *Penicillium verrucosum*, *Staphylotrichum coccosporum*, *Phoma* sp.,	Lis et al. (2004)
	France	Fungi 38 to 5.7×10^4 CFU m^{-3}	mesophilic moulds and *Aspergillus fumigatus*	Schlosser et al. (2016)
	Janik, Poland	Bacteria 1.7×10^4 CFU m^{-3} Fungii 1.8×10^4 CFU m^{-3}	*Pseudomonas* spp., *Staphylococcus warneri and Rhodococcus* spp., *Geotrichum candidum*, *Staphylotrichum coccosporum*, *Aspergillus niger and Myrothecium verrucaria*	Lis et al. (2004)
North America	Qubéc, Canada	Bacteria 10^3 to 10^4 CFU m^{-3} Moulds 8.3×10^3 to 9.871×10^4 CFU m^{-3}	Total bacteria	Lavoie and Dunkerley (2002)
	Mexico	Bacteria 9.7×10^3 to 5.1×10^4 CFU m^{-3}	*Staphylococcus aureus*, *Pseudomonas aeruginosa*, *Enterococcus faecalis and Escherichia coli*	Hurtado et al. (2014)
South America	Londrina, Brazil	Bacteria 1088.8 ± 825.2 CFU m^{-3} Fungi 2738.3 ± 1381.3 CFU m^{-3}	Not studied	Fernanda et al. (2020)
	Colombia	Fungi 73–1.83×10^3 CFU m^{-3}	*Aspergillus fumigatus*, *Aspergillus versicolor*, *Cladosporium* spp., *Geotrichum* spp., *Penicillium* spp. *Fusarium* spp.	Gamero et al. (2018)

outside the landfill site premises, operating and closed landfill cells, near leachate ponds, sorting facility, weighing station and social room. Results of the analysis showed that maximum concentrations of mesophilic bacteria (20–8.75×10^2 CFU m^{-3}), β-hemolytic bacteria (ND–60 CFU m^{-3}) and mannitol-positive bacteria (3–2.0×10^2 CFU m^{-3}) were near operating landfill cell. Some pathogenic species like *Pseudomonas aeruginosa*, *Bacillus cereus* and *Staphylococcus lugdunensis* were also occasionally detected in the indoor and outdoor air of the landfill site. The average number of microorganisms at landfill site was 2.5 times higher than the average numbers detected at the background site about 800 m away from the site. Schlosser et al. (2016) investigated the bioaerosols (mould spores) contamination from a landfill site in France. The waste tipping area reported the highest concentration of mesophilic moulds (4.8×10^5 CFU m^{-3}) and *Aspergillus fumigatus* (9.3×10^3 CFU m^{-3}) due to waste unloading activity. The study also found that concentrations of mesophilic moulds and *Aspergillus fumigatus* were higher than the bioaerosol concentrations in the local background even at a distance of 200 m and 500 downwind from the property boundary. Fraczek and Kozdroj (2016) reported that bioaerosols travelled only up to 100–200 m away from landfills. Breza-Boruta (2016) analysed the bioaerosols of landfill site situated in Northern Poland and reported the presence of fungi species *Aspergillus fumigatus, Aspergillus niger, Aspergillus terreus, Cladosporium herbarum* and the genus *Fusarium*. The total concentration of bacteria and fungi spores in the air within the facility ranged from 1.34×10^2 to 5.38×10^4 CFU m^{-3} and 1.21×10^2 to 1.829×10^4 CFU m^{-3}, respectively. The mycological analyses of the bioaerosols confirmed the presence of fungi like *Aspergillus fumigatus, Aspergillus niger, Aspergillus terreus, Cladosporium herbarum* and the genus *Fusarium.* Bioaerosols were transported up to 1250 m away from the landfill. Cyprowski et al. (2019) studied the spatial distribution of bacterial aerosol inside the landfill in Poland (Fig. 3) and found that bioaersol concentrations varied radially from the main operational area of the landfill. The maximum distance of bioaerosol travel was estimated to be 600–700 m from the landfill. These variations in the concentrations may be due to bio-meteorological conditions, quantity of waste and stage of degradation, affecting the bioaerosol dispersion.

4 Temporal variations in bioaerosol concentrations

Waste degradation in landfill sites results from complicated and symbiotic metabolic activities involving various groups of microbes (Krishnamurthi and Chakrabarti 2013). Periodic fluctuations in bio-meteorological and bio-climatic conditions like temperature, relative humidity, direction and speed of the wind, solar radiation play a vital role in the production, dispersion, viability and deposition of these microbes (Balyan et al. 2020; Kalwasińska and Burkowska 2013; Schlosser et al. 2016). The airborne microorganism can persist either as freely floating single or aggregation of cells or attached to dust or water droplets (Madhwal et al. 2020). After being aerosolized, bacteria can be conveyed up by convective air movements and can persist in the air for a considerable amount of time because of their small size (Smets et al. 2016). Similarly, concentrations of bioaerosols varied even during day and night time. In countries with temperate climate, low temperature in night combined with sufficient aeration provided significant dispersion of fungal spores (Odonkor and Mahami 2020).

Optimum microclimatic conditions for the proliferation of bacteria and fungi vary significantly. Most researchers from countries with temperate or continental climates reported higher fungal aerosols during the warm season compared to the cold season (Cyprowski et al. 2019; Fernanda et al. 2020; Fraczek et al. 2017; Madhwal et al. 2020). The humid environment supports maximum growth of bacteria, while fungi proliferate quickly in a dry environment (Hu et al. 2020). High relative humidity facilitates the fungal species to breed and form more compact colonies, leading to the lower release of fungal propagules into the atmosphere (Breza-Boruta 2016; Vilavert et al. 2012). Similarly, high temperature with low wind velocity and relative humidity restricts the transport of bioaerosols to the short distance which can

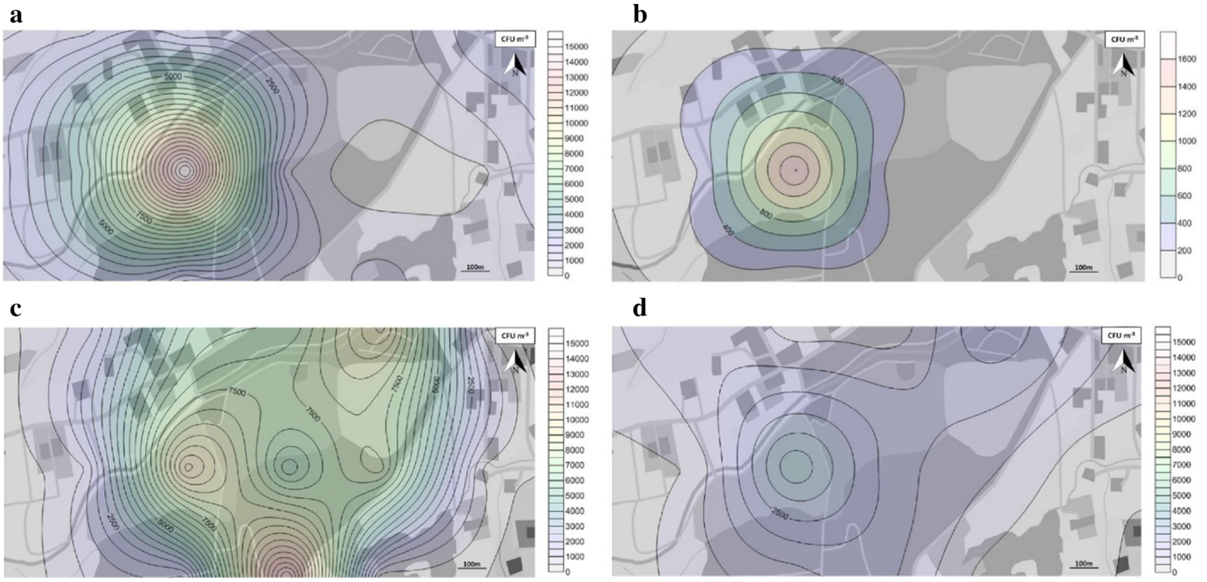

Fig. 3 Dispersion of bacterial aerosol inside landfill. **a** spring, TVB; **b** spring, GNB, **c** summer, landfill exploited, TVB; **d** summer, landfill standstill, TVB [Reproduced with permission from Cyprowski et al. (2019)]

peak the concentration of bioaerosols in the landfill and adjoining areas (Fraczek et al. 2017). Microclimatic conditions can also affect the biochemical characteristics of microbes. Higher temperature values, coupled with lower relative humidity, affect protein, nucleic acid and phospholipid membrane of microbes, preventing their growth and proliferation (Jones and Harrison 2004; Schlosser et al. 2016). The effect of microclimatic conditions on bioaerosol concentrations was noticeable in some studies. Cyprowski et al. (2019) reported the highest concentration of total viable bacteria in summer (temperature range 10–29.1 °C), while the levels of gram-negative bacteria were highest in autumn (temperature range 0.8–10 °C) in Poland. Similarly, Fernanda et al. (2020) analysed the bioaerosol levels in landfill sites located in Brazil for all three seasons and observed highest concentrations of airborne bacteria in summer and fungi in spring. Madhwal et al. (2020) also reported peak in fungal and bioaerosol concentrations during monsoon (temperature 29.14 ± 2.38 °C and RH 67.31 ± 8.64%), while winter (temperature 17.46 ± 3.0 °C and RH 34.83 ± 8.57%) witnessed a dip in the levels of bioaerosols released from Indian MSW landfill. Conversely, Huang et al. (2002) reported higher concentrations of fungal and bacterial bioaerosol during winter in Taiwan as the temperature and relative humidity range in winter was 23–27 °C and 69–72%, respectively.

5 Bioaerosol sampling techniques

Bioaerosols exhibit high fluxes in types and quantities, and hence, it is challenging to obtain representative samples. Bioaerosol monitoring demands efficient sampling technique for the collection of microbes from the air. A wide range of sampling and analytical techniques can be employed to determine concentrations of microbes in the atmosphere. Each sampling method has its requirements, advantages and disadvantages, and it is critical to consider them while employing these sampling methods. However, validation of the sampling efficiency is still uncertain (Pillai 2007). Sampling efficiency depends on species of microbes, components of the sampler, type and procedures of sampling methods (Burdsall et al. 2020). Also, samplers have differences in efficiency, sampling volume and size fractionation, influencing the results (Šantl-Temkiv et al. 2020). Sampling methods are broadly classified as passive and active sampling. In passive sampling, sterilized petri dishes with growth medium are exposed to ambient air for stipulated time (0.25–1.0 h) and later incubated at an appropriate temperature. The incubation temperature and media allow the microbes to form colonies which are eventually counted and identified (Delort and Amato 2018). Active sampling is similar to particulate matter sampling, which utilizes pumps to pull in the air. The primary active sampling methods are based on filtration, impaction, liquid impingement and electrostatic precipitation (Ghosh et al. 2015; Sharma Ghimire et al. 2019).

In the impaction method, sampler forces the airstream to abruptly change its direction due to which high inertia particles are trapped on the collecting surface. Collecting surfaces for bacteria and fungi are mostly agar plates (Ghosh et al. 2015). The main advantage of the impactor is that microbes collected on the medium can be directly incubated and later counted/analysed (Ghosh et al. 2015; Sharma Ghimire et al. 2019). However, sometimes agar plates are overloaded, and colonies may overlap, making it difficult to count (Ghosh et al. 2015). Also, impaction can cause injury to microbes, affecting the viability of bioaerosols (Pillai 2007). Six-stage cascade impactors were generally used for bioaerosol sampling, separate particle corresponding to their aerodynamic diameter. Each stage collects particles of decreasing size and has

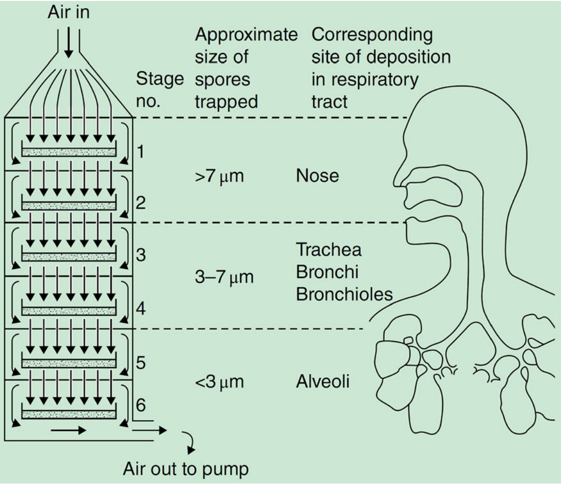

Fig. 4 Cut-off diameters of each stage of the cascade sampler and equivalent spots of deposition in the human respiratory tract [Reproduced with permission from Delort and Amato (2018)]

similarity with particle deposition in the human respiratory tract, as shown in Fig. 4 (Delort and Amato 2018). The cut-off aerodynamic diameters of stages in cascade impactors are > 7.0 μm, 4.5 μm, 3.3 μm, 2.1 μm, 1.1 μm and 0.65 μm, respectively (Delort and Amato 2018). The plates require no post-sampling processing and are incubated directly, and colonies are counted (Ghosh et al. 2015). The plates can also be subjected to microscopic examination for further analysis (Pillai and Ricke 2002).

Filtration sampler collects the microbes from the air as it passes through porous membrane filters (Ghosh et al. 2015). Filters are made of materials like gelatin, teflon, cellulose, polycarbonate, polyvinylchloride (PVC) or glass fibres (Ghosh et al. 2015). Filtration methods for bioaerosol sampling are comparatively economical and straightforward, enabling the collection of high-quality bioaerosol samples of wide-ranging particle sizes (Sharma Ghimire et al. 2019). However, sometimes overloading the filter makes it very difficult to enumerate the microbes (Ghosh et al. 2015; Sharma Ghimire et al. 2019). Also, drying of microbes collected on the filter is an issue with filtration techniques (Ghosh et al. 2015).

Impingers diffuse the air into a liquid medium using a vacuum to collect the airborne microbes into the liquid medium. After completing the sampling, the aliquots are transferred to the growth media for mining various microbes (Ghosh et al. 2015; Sharma Ghimire et al. 2019). The aliquots can be analysed by several methods including culture, molecular and microscopic methods (Pillai and Ricke 2002). It can also support advanced characterization methods like denaturing gradient gel electrophoresis to investigate the spatial and temporal variations in the bioaerosol diversity (Pillai and Ricke 2002). Impinger methods are mainly used for studying viable microbes as they are gentler than filtration or impaction (Delort and Amato 2018). However, significant disadvantages of this method are the evaporation of liquid medium which can restrict the duration of sampling and survival of microbes in the medium (Sharma Ghimire et al. 2019).

Ambient bioaerosol sampling at the landfill site is carried out at the height of 1.0–1.5 m above the ground level to simulate human breathing zone (Fraczek and Kozdroj 2016). Samples are normally collected on petri plates with growth medium, filter or liquid. Many aerobiologists have reported using six-stage cascade impactor for bioaerosol sampling in landfill sites (Akpeimeh et al. 2019; Fraczek et al. 2017; Fraczek and Kozdroj 2016; Kaarakainen et al. 2008; Lenart-Boron 2020; Madhwal and Prabhu 2020). The duration of sampling selected should be sufficient to produce 30–100 colonies per plate (Madhwal et al. 2020). Generally, the air is drawn at the rate of 28.3 L min^{-1} for 2–10 min when using cascade impactors (Akpeimeh et al. 2019; Fraczek and Kozdroj 2016; Madhwal et al. 2020). Few studies have also used impingers with liquid medium for bioaerosol sample collection in landfill sites (Capenter and Bidwell 1996; Pahren and Clark 2009; Sigsgaard et al. 1994). In case of impingers with a liquid medium, the sample is collected for 10–30 min at the flow rate of 12.5 L min^{-1}, to prevent dehydration of liquid medium (Ghosh et al. 2015). Filtration method is usually used in personal sampler due to the small size of instruments (Akpeimeh et al. 2019; Ghosh et al. 2015). After collections, samples are later transported to the laboratory in sterile sealed bags, for further analysis (Akpeimeh et al. 2019).

Recently, electrostatic samplers are also gaining the attention of aerobiologist for bioaerosol sampling. Electrostatic samplers suck the air into the sampler and charge the particles in the air. Later the charged particles are exposed to an electric field which neutralizes the charge and bioaerosols are deposited on the collecting surface (Delort and Amato 2018). The electrostatic sampler has high collection efficiency and induces comparatively less stress on the microbes during sampling due to lower particle deposition velocity (Delort and Amato 2018; Sharma Ghimire et al. 2019). However, the electric charge in the samplers can influence the microbial viability (Sharma Ghimire et al. 2019).

Additionally, new online methods like wideband integrated bioaerosol sensors (WIBS), spectral intensity bioaerosol sensor (SIBS), ultraviolet laser-induced fluorescence (UV-LIF) used for direct particle-counting can be used as alternative methods for the separate collection of bioaerosols (Ahmad et al. 2019; O'Connor et al. 2013; Robertson et al. 2019; Schlosser et al. 2016; Sharma Ghimire et al. 2019). Online methods characterize the auto-fluorescence of microbial particles to measure the morphology and optical size. Online methods can provide real-time, continuous bioaerosol monitoring data. However, the technology is still in its infancy (O'Connor et al. 2013).

6 Occupational exposure to bioaerosols and its health implications

In most conditions, landfill workers are exposed to a complex mixture of bioaerosols, organic dust and endotoxins. Bioaerosols responsible for human health hazards have particular biological characteristics, inhalation dose requirements, particle size distribution and chemical composition (Yates 2016). Some non-viable, non-infectious elements of bioaerosols can even initiate infections through harmful or immunopathological mechanisms (Yates 2016). Unfortunately, with limited dose–response data in conjunction with health information, it is challenging to evaluate the health impacts of bioaerosols. Various waste disposal activities on landfill sites can lead to microbial exposure of landfill workers through inhalation and dermal contact. Landfill workers and informal waste pickers hardly use any personal protective equipment and have significantly less opportunity to clean themselves during working hours, which put them at high risk of occupational hazards. Figure 1 illustrates the informal waste pickers handling waste in an open dumpsite. The workers can bring home the microbes through clothes and shoes and infect other members of the residence.

A large variety of airborne microbes attached to dust particles of size less than 7 µm, can easily reach the lungs (Kalwasińska and Burkowska 2013). Landfill site in Torun, Poland, reported the presence of *Salmonella, Clostridium perfringens* and coliform bacteria in the soil. The operating area of landfill reported coliform bacteria and *Clostridium perfringens* of concentrations 4–1226 MPN g^{-1} of the dry mass of soil and < LOD-1604 CFU g^{-1} of the dry mass of soil (Kalwasińska and Burkowska 2013). Workers involved in collecting household waste, and workers possessing the trucks with small loading height had the highest microbial exposure (Madsen et al. 2020). High concentrations of microbes have been reported inside the truck cabin, steering wheel and palms of the driver in vehicles used to transport waste (Madsen et al. 2020).

The most common health effects associated with the bioaerosol are respiratory symptoms and lung function impairment due to the exposure of organic dust, fungal spores, bacteria and faecal coliform (Yates 2016). Other health issues like skin and eye irritation, diarrhoea, nausea, fatigue, muscle pain, headache, joint pain, chills, fever, cough and chest tightness are prevalent among solid waste workers (Paulsen et al. 1995; Ray et al. 2005). The individual exposure to bioaerosols can be increased due to re-dispersion of organic dust collected on clothing, more expected in landfill workers (Koshy et al. 2009). Workers may moreover act as the carriers for microbial interceded respiratory illnesses (Madhwal et al. 2020). Exposure to these bioaerosols has a wide range of adverse health effects, including infections, immuno-allergic outcomes and toxic effects (Schlosser et al. 2016). Certain bioaerosol species can be the reason for lung diseases (Schlosser et al. 2016). Workers working near waste segregation, crushing, shredding, grading, sieving, conveyor transfer are exposed to the highest concentration of bioaerosols (Macklin et al. 2011). Exposure to organic dust increased the symptoms related to ODTS, which include fever, chill, fatigue, headache, dyspnoea, cough, joint pain and muscle ache (Perez et al. 2015). A study in India reported a prevalence of 39.6% breathlessness on exertion, 37.5% cough with phlegm, 34.3% dry cough and 12.5% wheezing among the solid waste workers. Similarly, another study in the Gambia reported 17.3%, 14.3% and 15.4% prevalence of cough, phlegm and wheezing, respectively (Darboe et al. 2015).

Fungi are a crucial element of bioaerosol. *Aspergillus fumigatus* is responsible for allergic bronchopulmonary aspergillosis, allergic alveolitis, sinusitis and asthma (Persoons et al. 2010). It is also accountable for 90% of invasive aspergillosis (IA) (O'Gorman 2011). The fungal spores and volatile toxic metabolites are responsible for allergic pneumonia, allergic rhinitis, asthma, chronic bronchitis and irritation of mucous membranes. Exposure to high concentrations of bioaerosols can induce fungal infection, cough, sneeze, diarrhoea, runny nose, throat irritation, skin ulceration and asthma exacerbation in people living nearby landfill site (Macklin et al. 2011; Ray et al. 2005). *Klebsiella pneumonia* exposure is linked to pneumonia, urinary tract infections and septicaemia (Pagalilauan et al. 2018). *Staphylococcus aureus* induces various diseases through to its presence on nasal passage, skin and axillae and also through enterotoxins and antigens (Pagalilauan et al. 2018). *Pseudomonas, Klebsiella and Haemophilus influenza* can cause lower respiratory tract infections (Madhwal et al. 2020). Exposure to *Mycobacterium tuberculosis*

(Mtb) can cause tuberculosis (Kim et al. 2018). The infections caused by *Microbacterium* spp. can result in significant mortality and morbidity (Heo et al. 2010). *Aspergillus, Penicillium* and *Fusarium* spp. also produce mycotoxins which can have an immunosuppressive, carcinogenic and toxic effect (Schlosser et al. 2020). *Aspergillus, Alternaria, Cladosporium, Penicillium and Candida* have been associated with severe persistent asthma (Baxi et al. 2016). Some of the common health hazards associated with airborne pathogens are presented in Table 2.

The aerodynamic diameter of bioaerosols plays a vital role in its dispersion in the atmosphere and deposition in various regions (tracheal, bronchial or the alveolar) of the human respiratory tract. Particles with the smaller size, i.e. 0.5–10 µm, can remain suspended in the air for longer duration and can be carried by air for longer distances affecting adjoining residents (Fraczek et al. 2017). Particles with an aerodynamic diameter greater than 4.7 µm are deposited in the nasal area, particles with aerodynamic diameter 2.1–4.7 µm are deposited in the bronchial area, while particles with an aerodynamic diameter less than 2.1 µm are deposited in alveoli of the lungs (Akpeimeh et al. 2019; Lenart-Boron 2020). The bioaerosol particles deposited in the mucous layer of bronchial airways required several days for complete removal. However, the particles reaching periciliary spaces underneath the mucous layer are cleared by slower mechanisms for instance uptake by alveolar macrophages or epithelial transcytosis which may be in the order of weeks to months providing an excellent opportunity for bioaerosols to exhibit their pathogenic potential (Aghaei et al. 2020; Sturm 2012). Akpeimeh et al. (2019) studied the particle size distribution of bioaerosols in an open dumpsite in Nigeria using six-stage sampler, which mimics the human respiratory system. Particle size distributions indicated that 41%, of total bacteria, 46% of gram-negative bacteria, 76% of *Aspergillus fumigatus* and 63% of total fungi were within respirable sizes and thus can penetrate deep into the respiratory system (Akpeimeh et al. 2019).

Table 2 Details of the pathogens associated with solid waste and their health hazards (Epstein 2015; Gao et al. 2018)

Genera	Pathogens	Health hazards
Aeromonas spp.	*A. hydrophila*, *A. veronii*	Diarrhoea, chronic enterocolitis, fever, vomiting and faecal leukocytes or erythrocytes
Actinomyces spp.	*A. israeli*, *A. bovis*	Allergic symptoms in the respiratory tract extrinsic allergic alveolitis
Bacillus spp.	*B. mycoides*, *B. pseudomycoides*, *B. thuringiensis*, *B. anthracis*	Food poisoning, gastroenteritis, tissue abscesses, endophthalmitis and anthrax
Bordetella spp.	*B. pertussis*, *B. bronchiseptica*	Pertussis or whooping cough
Entamoeba spp.	*E. histolytica*	Amoebiasis
Enterobacteria spp.	*Salmonella*, *Escherichia coli*, *Yersinia pestis*, *Klebsiella*, *Shigella*, *Proteus*, *Enterobacter*, *Serratia*, *Citrobacter*	Diarrhoea, severe damage to the lining of the intestine
Klebsiella spp.	*K. oxytoca*, *K. rhinoscleromatis*, *K. pneumonia*	Lung inflammation and haemorrhage
Micrococcus spp.	*M. roseus*, *M. denitrificans*, *M. colpogenes*, *M. flavus*	Recurrent bacteremia, septic shock, septic arthritis, endocarditis, meningitis and cavitating pneumonia
Mycobacterium spp.	*M. tuberculosis*, *M. leprae*, *M. africanum*, *M. avium*, *M. microti*	Tuberculosis, fever, night sweats, fatigue, loss of appetite and weight loss
Pseudomonas spp.	*P. aeruginosa*	Infect the blood, skin, bones, ears, eyes, urinary tract, heart valves and lungs, as well as wounds
Salmonella spp.	*S. enterica*, *S. bongori*	Diarrhoea, fever and abdominal cramps
Staphylococcus spp.	*S. aureus*	Produces enterotoxins which can cause nausea, stomach cramps, vomiting and diarrhoea, headache, muscle cramps
Aspergillus spp.	*A. fumigatus*, *A. flavus*, *A. niger and A. terreus*	Allergic fungal rhinosinusitis, allergic bronchopulmonary aspergillosis

Workers in the dumpsite had reported chronic wheezing and asthma (Akpeimeh et al. 2019). *Aspergillus fumigatus* are usually of 2–3.5 µm in diameter (Akpeimeh et al. 2019).

Apart from the fungi and bacteria, the exposure to the toxic metabolites produced by these microbes is also responsible for serious health concern. Gram-negative bacterial cell wall produces endotoxins during multiplication, growth and death (Maharia and Srivastava 2020). Bacteria produce endotoxins that can lead to chills, fever, fatigue, headache, joint pain, fluctuations in the number of leukocytes in the blood, dry cough, upper airway inflammation, bronchial asthma, ODTS and the acute form of byssinosis, systemic inflammatory response and death (Kozajda et al. 2017; Liebers et al. 2008; Madhwal et al. 2020; Park et al. 2011). Endotoxins are major contributors to occupational lung diseases and ODTS (Kim et al. 2018). Endotoxin attached to organic dust gets inhaled and precipitated in the lungs and induces several acute and chronic respiratory symptoms and gastrointestinal disorders (Aghaei et al. 2020). During waste handling, even low exposure of endotoxins and medium exposure fungal spores and ß-glucans can lead to inflammation in upper airways (Darboe et al. 2015). Inhaling more than 80 mg of endotoxins can reduce lung function (Kim et al. 2018). Similarly, glucans may induce immunosuppressive and inflammatory reactions (Kozajda et al. 2017). Fungi produce toxic, low molecular weight non-volatile secondary metabolites, commonly referred to as mycotoxins (Schlosser et al. 2020). Mycotoxin ingestion can lead to immunosuppressive effect and cancer (Schlosser et al. 2020). *Aspergillus fumigatus* can produce a large quantity of small-sized (2–3 µm) mitotic conidia which can reach the human lung alveoli through inhalation (O'Gorman 2011). D-glucan existent in the cell wall of the *Aspergillus fumigatus* suppresses the immune system and intensifies the sensitivity to allergens. Other means of access include eyes, ears and broken skin (O'Gorman 2011). Mycotoxins produced by *Aspergillus* and *Penicillium* also have harmful effects on respiratory health (Madhwal et al. 2020). *Clostridium perfringens* produces toxins and is also causative agents of gas gangrene (clostridial myonecrosis), enteritis necroticans, food poisoning and non-food-borne gastrointestinal infections (Kalwasińska and Burkowska 2013; Rood 1998). Rahkonen et al. (1990) reported 0.4–29 ng m^{-3} of endotoxin released from two landfill sites in Finland. Ivens et al. (1999) conducted exposure study on 2303 male waste collectors in Denmark and reported that the workers exposed to the high concentration of endotoxins and fungi frequently reported nausea, diarrhoea and gastrointestinal problems. Park et al. (2011) carried out the exposure study among the landfill workers in South Korea and found that 35% of landfill workers were exposed to endotoxin level higher than 1000 EU m^{-3}, which is regarded as the dangerous level of exposure (Park et al. 2011). Furthermore, endotoxin exposure level among workers sorting recyclable waste was over 2000 EU m^{-3}. Also, the exposure level of landfill workers to fungi ranged from 2.4×10^4 CFU m^{-3} to 10.8×10^4 CFU m^{-3} (Park et al. 2011).

Furthermore, active growth of fungi can produce more than 200 volatile organic compounds, known as microbial volatile organic compounds (MVOC) (Persoons et al. 2010; Yates 2016). MVOCs are mostly derivatives of amines, alcohols, aromatics, esters, aromatics, hydrocarbons and sulphur-containing compounds which are abundant in MSW disposed of in landfill (Yates 2016). For example, *Penicillium* and *Aspergillus* can produce 2-methyl-1-propanol, 2-methylisoborneol, 3-methyl-1-butanol and 3-octanone (Yates 2016). MVOC exposure can result in irritations in upper airway, eyes and skin.

7 Future perspective

Every landfill site is distinctive about the amount and nature of waste disposed, stage of waste degradation, local meteorology and engineering practices. Local biometeorological conditions like temperature, pressure, relative humidity, wind direction and the composition of waste and leachate generated can significantly affect the survival and multiplication of pathogenic agents (Schlosser et al. 2016). Hence, the results of the microbial concentrations from these landfill sites should be assessed with caution. Regardless of the terrestrial positions of the landfills or the process employed to establish the microbial diversity, an observation common in the literature was that bacterial members of the phylum *Firmicutes* were strongly predominant in landfill atmosphere, followed by *Actinobacteria* and *Proteobacteria.* It is essential to understand the spatial and temporal patterns of exposure to evaluate the potential health risks.

Though the previous researchers have excellently studied the extensive array of microbes, the microbial communities in real landfill sites are yet to be wholly exposed as there are several complications in sampling and analysis. The existing bioaerosol monitoring methods are tedious, expensive and time-consuming with very low reproducibility (Leuken et al. 2016). Aerosols in the landfill environment consist of a composite mixture of different microbial aggregates, all of which were not analysed by the researchers. The microbes identified depending on the methods adopted for sampling and analysis, which are very specific for many microbial species. Moreover, bioaerosol and endotoxin analysis needs skilled personnel. Hence, a modern approach like real-time biosensors and online autofluorescence can help acquire high-resolution data (Sharma Ghimire et al. 2019). Also, atmospheric dispersion models can facilitate scientists to simulate bioaerosol dispersion (Leuken et al. 2016). Using tools like risk assessment and life cycle assessment can help the authorities understand the quantity and negative impacts of bioaerosols in landfill sites (Fattor et al. 2019). The outcomes of health and safety analysis can aid the authorities in designing suitable interventions.

Limited epidemiological evidence is linking increased health risks among landfill workers and bioaerosol exposure. As the health effects triggered by the microbes vary significantly at the species level, it is challenging to develop occupational exposure limits for fungal and bacterial exposure. Moreover, even deficient exposure levels can exacerbate the symptom in workers with pre-existing respiratory issues. Many of the exposure studies have limited samples, making it challenging to correlate the exposure of microbial species to the symptoms statistically. These studies also lack information about the potential confounders like age, sex, employment duration, lifestyle habits—smoking, consumption of alcohol, diet, residential environment and socio-economic status, and presence of other pollutants in landfill sites. These factors can lead to misleading results. For instance, microbes may be bound to particulate matter in the landfill site, which itself can induce health hazard (Koshy et al. 2009). Hence, added studies are essential to correlate the microbial species with occupational health hazards statistically.

The landfill workers are exposed to a complex mixture of bioaerosols, dust, VOCs and other compounds. The waste management industries need to heighten management efficiency and increase the effectiveness in complying with legal, environmental and occupational safety standards. The literature reveals that landfill workers are directly exposed to high concentrations of bioaerosols leading to several occupational hazards. Their main route of exposure to microbes is through inhalation and dermal contact (Madsen et al. 2020; Ray et al. 2005). Workers rarely practise protective measures and personal hygiene. Lack of leadership and safety plans also aggravates the situation. Sometimes, the workers' casual approach leads to low-quality PPE procurement and their inappropriate use (Thakur et al. 2018). Hence, government authorities must provide an appropriate legal framework regarding workers' safety in solid waste industries. Proper guidelines should be framed for the quality standards of PPEs used in the landfill sites (Battaglia et al. 2015). Also, management should ensure an adequate supply of high-quality PPE with engineering controls such as HEPA filtration, ultraviolet irradiation and photocatalytic processes to filter and inactivate the bioaerosols in the atmosphere (Rodrigues-silva et al. 2016). Also, waste management industries should focus further on training the workers about the pathogen emission, host-susceptibility and various health hazards associated with the bioaerosols in the working area. Regular training and monitoring can improve the employees' attitude towards personal safety and hygiene. Practising personal hygiene like cleaning themselves before leaving the landfill site and consuming food can reduce the number of microbes entering their respiratory and intestinal tract. Madsen et al. (2020) reported that landfill workers' palms contain up to 270 CFU hand^{-1} of fungi, up to 1800 CFU hand^{-1}of yeast and 4×10^2–4.1×10^4 CFU hand^{-1} of bacteria. Studies have proved that regular use of hand sanitizers by workers can significantly reduce microbial exposure through hands (Madsen et al. 2020). Providing water, sanitation, vaccination and proper health care can improve workers' quality of life and reduce occupational hazards due to bioaerosol exposure. Despite the high risk in waste handling activities, vaccination rates among the solid waste workers are low (Black et al. 2019). Regular cleaning of the equipment used to handle the waste and sanitizing the steering wheels and handles can also reduce the microbial exposure in the equipment/truck cabin.

8 Summary

Studies have remarkably reported the presence of various species of pathogenic bioaerosols in the landfill environment. The quantity and nature of bioaerosols are influenced by various factors like location, type of waste, age of waste and degradation stage. Landfill sites loaded with pathogenic microbes can become the centre for the epidemic outbreak with the highest risk infection to the workers and adjoining residents. The employees are exposed to elevated concentrations of bioaerosols from the various waste management activities in landfill site mostly via the inhalation and hand to mouth. In light of this, additional investigations are required to create improved assessment tools for bioaerosol exposure and validation. Previous studies have sucessfully correlated bioaerosol exposure and health issues like irritation of eyes and musculoskeletal problems, respiratory symptoms and gastrointestinal problems. However, more investigations are required to obtain the exact mechanism and dose–response relationship for bioaerosol exposure. Workers' exposure to landfill bioaerosol is a critical voiced problem in public health and occupational medicine and hence has been a concern for governing authorities. Advanced instruments for real-time monitoring of bioaerosols can be deployed in the landfill site to obtain high-resolution data with spatial and temporal variations. Adequate training is essential to ensure employees to understand the health risk due to contaminant exposure practice personal safety. Detailed risk assessment study and implementation of intervention plan are essential to safeguard the health of workers and adjoining residents.

Compliance with ethical standards

Conflicts of interest Not applicable.

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