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Assessment and Control of Bioaerosols in Indoor Environments

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ABSTRACT

Bioaerosols, which are composed of a diverse array of biological materials such as bacteria, fungi, viruses, allergens, and microbial byproducts, are ubiquitous in indoor environments, as well as outdoor environments. These agents, which may be viable or non-viable, can contribute to a variety of health issues depending on exposure levels and the individual's susceptibility. Bioaerosol hazards are complex to assess due to the variability in agent types, concentrations, and health responses. Effective evaluation involves understanding source-pathway-receptor interactions, considering both outdoor and indoor bioaerosol contributions, and employing a scientific method to determine potential health risks. Bioaerosol assessments must combine a thorough visual inspection to identify contamination sources and prevent future issues with an evaluation of environmental data and a risk analysis. Effective assessment and control of bioaerosol exposures in indoor environments require clearly defined hypotheses, emphasizing the need for professional expertise in microbial sampling techniques. The industrial hygiene hierarchy of controls, along with decision matrices and control banding frameworks, provides a structured approach for selecting appropriate protective measures to mitigate bioaerosol risks.

INTRODUCTION

Bioaerosols may consist of molds/fungi, bacteria, pollen, mites, viruses, spores, and cellular membrane components, as well as variety of different volatile and non-volatile metabolites and byproducts of cells (ACGIH, 2025). Bioaerosols, which may or may not be viable (i.e., capable of reproducing or remaining alive and infectious), include airborne fragments, propagules, and chemical compounds from biological organisms, including plants, animals, viridae, bacteria, and arthropods. They can include fragmented bodies and feces from insects, including cockroaches and dust mites, as well as allergenic proteins present in the saliva, dander, and urine from pets (i.e., cats, dogs) and other furred animals (Flannigan, 2001). Bioaerosols also potentially consist of various cellular components (e.g., chitins, endotoxins, glucans), non-volatile secondary metabolites (e.g., mycotoxins), microbial volatile organic compounds (mVOCs), antigens, and/or allergens that arise from microbial metabolic activity or the decomposition of nutrients and substrates (ACGIH, 2025).

The American Conference of Governmental Industrial Hygienists (ACGIH) uses the term ***biological agent*** to refer to a substance of biological origin that is capable of producing an adverse health effect, such as an infection or a hypersensitivity, irritant, inflammatory, or other adverse response (Marcham, 2024). Mold spores and gram-negative bacteria are introduced to the indoor environment from the outdoors by a variety of ways including the outdoor air intakes for the ventilation system, open windows and doors, on occupant clothing and footwear, and even by simply attaching to dust particles (Gravesen et al., 1994; Burge, 1987). Humans are commonly exposed, day after day, to a wide variety of biological contaminants at variable

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concentrations, typically at levels that do not necessarily elicit an adverse health response or otherwise result in injury or disease. However, while microbiological agents are ubiquitous in nature and generally do not cause harm, some may become amplified and pose a potential health risk to occupants in damp indoor environments as well as from water damaged materials. How, then, do mechanical engineers and other indoor environmental professionals assess whether bioaerosols in an indoor environment are a health concern, and whether control of such bioaerosols is called for?

RISK ASSESSMENT OF BIOAEROSOL HAZARDS

Assessing the hazards and risks associated with exposure to bioaerosols presents many unique challenges. When evaluating whether bioaerosols are a concern, it is important to use and apply the concept of the source-pathway-receptor paradigm (Figure 1). Sources of indoor bioaerosol agents can include those from outdoors, such as nearby agricultural activities or composting facilities, as well as indoors, such as microbial growth on wet building materials or even the occupants themselves. In general, the fungal population and diversity of the air inside a building is a function of the amount of outdoor air that is used to ventilate the building (Hargreaves & Parappukkaran, 2000). Absent some specific indoor source of bioaerosols (e.g., microbial growth), airborne levels will generally be lower than those found outdoors, particularly in mechanically ventilated buildings (Muilenberg 1995) As a general rule, the indoor air in dry, non-problem buildings should contain a mixture of leaf-derived, or phylloplane, fungi, (i.e., *Cladosporium*, *Alternaria* and *Epicoccum*) that are normally present in the outdoor air (Flannigan & Morey, 1996; Morey 1999). Comparison of the indoor and outdoor bioaerosol concentrations, therefore, can be a possible indicator of whether or not microbial amplification is occurring in the building. The significant presence of fungi in the indoor environment, which are either not present or just a minor component of the outdoor air, should be considered unacceptable from both a health perspective and a building performance point of view (Miller, 1993).

Figure 1 Source – pathway – receptor paradigm

Indoor exposures to bioaerosol can occur through multiple pathways (routes), but the primary route is via inhalation. Hazard and risk assessments for biological agents are complicated, however, by variabilities in both the types and concentrations of bioaerosol agents, as well as the individual receptor's susceptibility and response to those agents. Unlike exposures to chemical agents (e.g., benzene), which for the most part have relatively consistent properties, biological responses, and subsequent health effects, in many cases the biological agent in question may be, in fact, a non-homogenous mixture of different biologically derived materials, in varying concentrations, reflecting the diverse and interactive nature of indoor microenvironments (ACGIH, 2025). For example, indoor sources of microbiological growth and contamination often consist of multiple different genera and species of fungi and environmental bacteria, along with their various components, byproducts, and metabolites, as well as the damp substrates supporting their growth (Flannigan & Miller, 2001).

While researchers and others often use the singular term "endotoxin," the substances classified as such are a single substance and vary greatly. Endotoxins are members of a class of phospholipids, called lipopolysaccharides, and are a component of the outer cell wall membrane of gram-negative bacteria. They can consist of a variety of different structures, with differing molecular weights and toxicities, depending on the genus of bacteria from which they arise (Di Lorenzo et al., 2021; Raetz & Whitfield, 2002; Thorne et al., 2016). Endotoxins are potent stimuli of inflammatory and immune system responses and are believed to be an important contributor to occupational respiratory disease, particularly in agricultural settings. The ACGIH recently adopted a threshold limit value (TLV) of 90 endotoxin units per cubic meter of air (EU/m^3), which has come under scrutiny and criticism (Springston & Marcham, 2024). Airborne endotoxin levels are generally correlated with exposure to other bioaerosol components, such as fungal spores and fragments, and the nature of exposures in different occupations are vastly different (Farohki et al., 2018).

Mycotoxins are non-volatile, low molecular weight secondary metabolites that are naturally produced by certain filamentous fungi, which are known to cause illness in humans and animals, primarily after ingestion of large quantities of fungal-contaminated foods (Smith & Solomons 1994; Peraica et al. 1999; Stoev 2015; Miller 2016). Mycotoxins and other secondary metabolites are species specific, as well as limited to particular strains or chemotypes within species (Bennett and

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Klich, 2003). Production of fungal secondary metabolites usually initiates later in the growth of the microorganism and is frequently associated with sporulation processes (Bu'Lock 1961; Sekiguchi & Gaucher 1977). Water is perhaps the most limiting factor with regard to mycotoxin production, as significant quantities are not formed until substrate water activity (a_w) reaches 0.95 or greater (Cahagnier et al., 1995; Nielsen, 2003). It is important to note, however, that while all mycotoxins are fungal secondary metabolites, not all secondary metabolites from fungi are mycotoxins. An estimated 15,600 bioactive metabolites of fungal origin have been described (Bérdy 2012; Bills & Gloer 2016)). Out of that number, over 300 mycotoxins had been identified, but only 30 have been subjected to research aimed at highlighting their toxic properties (Viegas et al., 2018). A number of fungal secondary metabolites are in practical use for human therapy as antibiotics, antivirals, anti-inflammatory, antineoplastic/antitumor, enzyme inhibitors, hypercholesteremic, and immunosuppressant agents (Nielsen and Nielsen, 2017; Conrado et al. 2022).

Airborne concentrations of fungi and other bioaerosols are highly variable, both spatially and temporally, as well as seasonally and activity-based (Verhoeff et al. 1990; Pasanen et al. 1992; Li & Kendrick 1995; Hyvärinen et al. 2001; Chew et al., 2001; Crawford et al., 2009; Hung et al., 2020;). Miller (1993) reported that airborne culturable fungi, collected over the course of a day in a classroom, showed a variability of four orders of magnitude, with levels ranging from non-detectable to nearly 1500 colony forming units per cubic meter (cfu/m^3). When using semi-quantitative collection devices, such as spore trap samplers, variations of as much as 1,000-fold can occur between essentially identical samples (Hung et al. 2021). Given these spatial and temporal variations, and the short sampling time (typically 1-10 minutes) for most bioaerosol sampling methods, it is difficult, if not impossible, to quantify occupant exposures with any accuracy or precision.

In addition to the various bioaerosol properties that can affect an agent's infectiousness, transmissibility, allergenic or inflammatory potential, etc., the health response(s) of the individual exposed may also vary depending on health status, sensitivity, preexisting conditions, and a host of other factors. While some case studies of affected workers, epidemiological studies of groups of workers, laboratory and clinical evaluations, looking at adverse health effects arising from certain bioaerosol exposures are available, it is very difficult to demonstrate consistent relationships between direct quantitative microbiological measurements in buildings and health effects in occupants (Mendell & Adams, 2019). Unfortunately, these variations in bioaerosol agent properties, and in exposed receptor sensitivities and health outcomes, make establishing generic health-based occupational exposure limits (OELs) for most bioaerosols, particularly those that do not exist as single compounds, extremely challenging, if not virtually impossible (Strode et al., 2024).

All of these issues prohibit the identification of elevated or excessive bioaerosols exposures by solely measuring airborne concentrations of biological agents. Rather, investigators identify associations and correlations between bioaerosol exposures and occupant health effects on a case-by-case basis, by combining hazard and risk assessments, as well as environmental observations and measurements.

ENVIRONMENTAL OBSERVATIONS

ACGIH (2025) defines indoor ***biological contamination*** as "the presence of: a) bioaerosols likely to cause or predispose humans to health effects; b) inappropriate indoor airborne concentrations of bioaerosols, as determined through the consideration of space type or occupancy purposes; or c) indoor microbial growth, amplification, or remnants of biological growth, or sources of infectious agents or pathogens, deposited, accumulated, or amplified, that may become aerosolized and to which humans may be exposed." The mere presence of microbiological materials on surfaces, however, does not necessarily mean that contamination is present. For mold, the presence of some spores and mycelia/hyphal fragments, particularly soil and phylloplane-related fungi, on interior surfaces and furnishings is typical of normal deposition and not necessarily evidence of fungal colonization (Hung et al., 2005). Indeed, the Institute of Inspection, Cleaning and Restoration Certification (IICRC), in its S520 Standard for Professional Mold Remediation, defines a Condition 1 indoor environment, relative to mold, as one "that may have *settled* [emphasis added] or airborne mold spores or fragments, or traces of actual mold growth and constituents, that are reflective of a clean and dry environment" (IICRC, 2024). The key distinction between settled, dormant spores on a surface and a colonized material is entirely dependent upon whether or not sufficient moisture (i.e., bulk water or water vapor) was available at some point to initiate and sustain microbial growth (Springston et al. 2021).

When assessing whether bioaerosol contamination is a concern, the steps taken should generally follow the scientific method, as depicted in Figure 2. When investigating complaints regarding damp indoor environments, "testing" of a hypothesis involving microbiological growth and contamination often requires no more than a thorough, informed visual and olfactory

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assessment of the environment in order to come to a reasonable conclusion as to what is likely occurring. Other times, certain environmental measurements (e.g., moisture measurements of affected building materials, water activity on surfaces, relative humidity levels, etc.), along with air, source, and/or settled dust sampling, may be warranted and justified. Factors to consider include, but are not limited to, whether or not the sample results will affect the inspection outcome or remediation recommendations, legal implications of potential findings, if a validated sampling and analytical method exists, and if the sampling will provide a statistically sound basis on which to evaluate the hypothesis (Weekes, 2024).

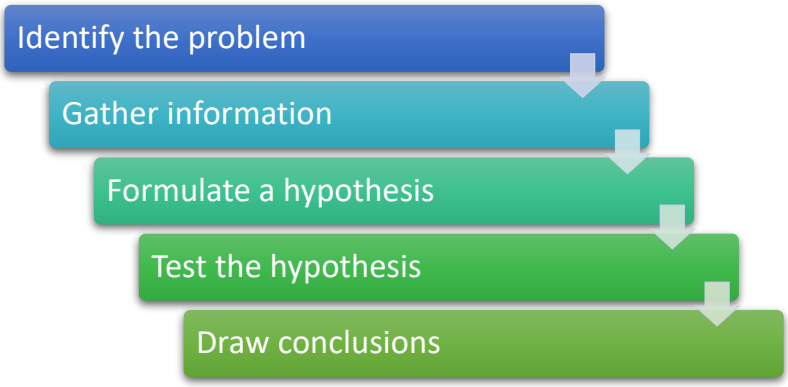

Figure 2 The scientific method

Bioaerosol assessments should be designed to answer specific questions regarding the indoor environment, not just to collect samples, and strive to understand the interactions between the occupants, contaminants, and surrounding environment (Cull, 2024). The purpose of a bioaerosol assessment should be to 1) identify potential microbial issues and problems, 2) determine the root cause(s) of the problems, 3) formulate a remediation plan, and 4) note areas that may be susceptible to future problems. A good remediation plan will detail not only those materials that are contaminated and need to be removed, but will also help identify the measures needed to correct the root cause of the problem and prevent it from occurring again in the future. Additionally, the assessor should attempt to identify any potential pathways (e.g., stairwells, elevator shafts, etc.) and pressure differential relationships that may directly, or indirectly, connect the contaminant sources to the occupants.

For mold and moisture assessments, during the initial building inspection the investigator will visually assess the entire structure of the building, inside and out, to identify any evidence of water damage or uncontrolled moisture, including suspect visible microbial growth. Microbial growth may be obvious on surfaces within the occupied space, or may be located within crawlspaces, wall cavities, inside heating, ventilating, and air-conditioning (HVAC) systems, or other “hidden” locations with conditions conducive for growth. Clearly, if widespread visible microbial growth and strong musty odors are present, then there is little doubt that a problem exists. In some cases, though, what may appear to be microbial growth is, in fact, not, so caution must be exercised when verifying the presence of such growth. It should also be noted that the mere presence of visible microbial growth does not necessarily mean that occupants are exposed to spores, fragments, metabolites, or other biological agents from that growth, or that any health symptoms or problems that occupants may be experiencing are due to the presence of that growth. The investigator should not assume that bioaerosols are being generated, or that occupants are being adversely affected, based solely on observational data.

ENVIRONMENTAL SAMPLING

In most cases, when investigating and evaluating indoor mold and moisture issues, the collection of environmental samples is unnecessary and, in most cases, generally not recommended (NYCDOHMH, 2008; EPA, 2008; NIOSH, 2012). This is particularly true for routine assessments, or when bioaerosol sampling will not add any additional information beyond that which is collected during a thorough visual inspection conducted in accordance with accepted standards, such ASTM 7338-14: Standard Guide for Assessment of Fungal Growth in Buildings (ASTM, 2014). The assessment of bioaerosols in an indoor environment should be conducted by an experienced, qualified, and well-educated investigator who has the necessary investigative tools, if needed, to supplement the visual inspection. Obviously, the skills and knowledge required to conduct a

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competent bioaerosols assessment cannot simply be attained by attending a basic mold training class conducted over one or several days (Hung et. al. 2021).

For several decades now, numerous authorities have noted that uncontrolled microbial growth in occupied built environments is unacceptable, that such growth should be removed, and that further growth should be prevented (Maroni et al. 1995; Clark et al., 2004; EPA, 2008; Hung et al., 2020). If widespread visible microbial growth is present indoors, there is often little or no benefit in collecting samples, especially short-term air samples for estimating occupant exposure. Resources should instead be used to isolate, and remediate the source of the bioaerosols, and, perhaps even more importantly, to identify and correct the root cause of the problem. For indoor microbial growth, that typically means the source of the water or moisture condition that caused the growth, while for viruses and other infectious agents it may entail vaccination.

The lack of OELs or other health-based standards or guidelines for most biological agents precludes the collection of bioaerosol samples and then simply comparing the results against established air concentrations. Air sampling may be performed to identify and quantify/semi-quantify certain bioaerosols, identify and verify the release of bioaerosols from a source, assess and calculate exposure to an agent, or monitor and confirm the effectiveness of a control measure, but bioaerosol sampling cannot be used to estimate or project possible health effects. Air sampling should also not be the sole method used to test a hypothesis regarding the presence of indoor microbial growth, be it visible or hidden. Bioaerosol sampling, however, can be a useful supplement to a thorough informed visual inspection that also includes bulk, swab, and/or tape lift samples from suspect microbial growth sources.

At the start of an assessment, the investigator must clearly define their hypotheses and determine what data is needed and appropriate, and what information will be gleaned, through the collection of any environmental samples (Weekes, 2024). If such sampling is to be performed, a detailed written sampling plan should be prepared that includes equipment selection and handling, when and where to collect samples, the number and type of samples, sample times and flow rates, and other relevant information. Sampling should only be conducted by professionals with specific experience in designing microbial sampling protocols, the various sampling methodologies used, and interpretation of the results (EPA, 2008). Bioaerosol samplers use one of three methods of particle collection, namely filtration, impaction onto a solid media (e.g., agar plate), or impingement into some type of liquid media. Common to all bioaerosol samplers, though, is consideration for collection efficiency, including inlet sampling efficiency, particle removal efficiency, biological recovery efficiency, and assay efficiency, as well as a multitude of other factors affecting sampler performance (Springston, 2022).

REMEDITION AND CONTROL STRATEGIES

Selecting appropriate and effective control measures can be challenging for the safety and health practitioner, as selecting appropriate control measures depends on the nature and the source(s) of the bioaerosol(s) of concern. The general principles for preventing and controlling indoor microbiological growth are 1) prevent colonization of materials and systems within the building; 2) limit infiltration of bioaerosols from outdoors; and 3) minimize indoor accumulation of bioaerosols from humans and animal sources (Lstiburek & Springston, 2024). Removal of the bioaerosols source is obviously the best way to eliminate the hazard. However, for some infectious agents, such as influenza or COVID-19, the source may be the building occupants themselves, so elimination of these infectious agents is not a viable option.

Remediation work involving indoor microbial growth must be clearly defined and the extent delineated. Determining if contents and materials can be effectively and adequately cleaned can be a critical, and contentious, question. Most remediation efforts involving more than 10 square feet of visible growth should be conducted with independent oversight and some form of post-remediation verification, be it just a visual and olfactory assessment or also include sampling (Springston & Krause, 2024). Following any remediation work, building managers should implement a long-term plan to prevent reoccurrence of the problem, as well as a regularly scheduled cleaning program to control the buildup of contaminants and settled particles (Lstiburek & Springston, 2024).

Buildings are dynamic environments that are affected by a host of different factors including, but not limited to, geographic location, season, weather conditions, HVAC system design and operation, building envelope condition, pest colonization, and human activities (Lstiburek & Springston, 2024). As a result, conditions suitable for microbial growth or transmission of infectious diseases are continually changing. Additionally, the interactions of various microorganisms with both each other, and with their environment, result in fluctuating airborne microorganism populations and concentrations over time, rather than stable, constant exposures. Measures to limit and minimize microbial colonization and growth on building

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materials typically focus on moisture control and maintaining levels below that necessary for microbial growth. Some of the primary means of moisture entry into buildings include water leakage, air infiltration, vapor migration, capillary movement, and bypass of HVAC dehumidification cooling coils (Lstiburek & Springston, 2024). Prompt response to moisture intrusion and other water damage, including drying of affected materials, can prevent or limit mold and bacterial growth (EPA, 2012).

Ventilation

The concentration of bioaerosols in a space is related to a multitude of factors including, but not limited to, the source type, the number of sources, the rate at which those sources are generating bioaerosols, the rate at which the bioaerosols die, become inactivated, deposit, or are somehow removed (Strode et al., 2024a). While source control/elimination is a preferred and more effective control measure for infectious agents, mechanical ventilation, when properly designed and operated, plays a critical role in reducing and controlling the dissemination of bioaerosols and other airborne contaminants. The two primary types of ventilation used to remove, and therefore reduce, the level of airborne contaminants are local exhaust ventilation (LEV) and general ventilation. LEV involves the capture and removal of contaminants generated within a space, typically at or as close to the source of generation as possible, using various devices (e.g., fume hoods, fume extractors). Other common examples of LEV in buildings include kitchen range hood and bathroom exhausts. LEV is more frequently used in industrial, laboratory, educational, and health-care settings.

General ventilation, rather than focusing on the exhaust of contaminated air, emphasizes the supply of conditioned air to the occupied space primarily for comfort purposes. The intent of general ventilation is to either replace or dilute volumes of contaminated air with “clean,” outside air, and/or filtered recirculated air, to reduce the contaminant levels below a particular regulated or recommended concentration to avoid overexposure and adverse health effects (ACGIH, 2021). Factors that determine the effectiveness of a system to reduce contaminant levels, or to lower the risk of airborne transmission of an infectious disease, include the amount of outdoor air being introduced into the system, as well as the level of filtration of the recirculated air. With general ventilation, airborne contaminants can be removed and reduced via one of two different and distinct airflow arrangements: 1) dilution ventilation and 2) displacement ventilation.

Dilution ventilation, sometimes described as turbulent flow or mixing ventilation, mixes (and thus, dilutes) contaminated air with clean air to lower the concentration of any airborne contaminants within the space to avoid adverse reactions and health effects. Conditioned air is supplied at relatively high velocities from air diffusers, typically located at ceiling height, with the return air grilles commonly also located at ceiling height. The idea is to supply air in a manner such that the entire volume of air within the space is fully mixed, thereby making contaminant concentrations uniform throughout and minimizing temperature variations. As previously noted, though, most biological agents do not have widely accepted health-based OELs or guideline values. Therefore, if dilution ventilation is the only control method available, it is most effective when using as much “clean” outdoor and sufficiently filtered recirculated air, and with as complete air mixing as possible.

Displacement ventilation minimizes overall room air mixing, and instead “pushes” away contaminants in as near to a laminar directed plug flow as possible (ACGIH, 2021). With displacement ventilation, conditioned air is supplied at low discharge velocity from air diffusers located at or near floor level, and the return air grilles are typically located at ceiling height. The idea is to use thermal plumes from occupants, electrical equipment (e.g., computers), and other heat sources to pull the contaminated air up and away from the breathing zone and replace it with “clean” air. Displacement ventilation has been recommended as one of the potentially more effective interventions, when used in a layered approach, to minimize occupant exposures to highly infectious agents (Bhagat & Linden, 2020; Lipinski et al., 2020).

Air Cleaning Devices

Portable air cleaners, also referred to as air purifiers or air sanitizers, can help to reduce the concentrations of bioaerosols and other air contaminants within a single room or limited area. Standalone air cleaners, such as portable HEPA-filtered units, can be used to supplement ventilation provided by HVAC systems to achieve increased effective air change rates (ASHRAE, 2021; CDC, 2019; AIHA, 2020). In order to be effective, though, air cleaners must be appropriately sized for optimum particle removal. The rate of air filtration through the air cleaner must be greater than the source emission rate, the device must be capable of filtering and delivering a sufficient volume of clean air for the size of the space, and the placement of the units must not interfere with existing HVAC systems (ACGIH, 2021a). Guidance on determining the appropriate number and size of air cleaning devices, based on room size and clean air delivery ratings (CADR) ratings (AHAM, 2014), are available elsewhere

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(ASHRAE, 2021a; CDC, 2021; AIHA, 2021).

Ultraviolet germicidal irradiation (UVGI) technology has been used since the 1930s as a "no-touch" method of reducing airborne concentrations of infectious agents and other bioaerosols (Reed, 2010). The germicidal action of UV light has been demonstrated, to varying degrees, for viruses, bacteria, and fungi, with some biological agents being more resistant than others (Kowalski, 2010). UV lights can be installed on the upper section of walls (i.e., near the ceiling) inside occupied rooms, as well as inside HVAC systems. For upper room UVGI, good vertical air mixing is required to bring any bioaerosols present the room into contact with the UV light for effective use (First et al., 1999). For in-duct applications, a balance between duct size, airflow rate, and residence time in the UV light zone must be achieved to allow sufficient light contact time for inactivation, while also allowing sufficient supply air volume to meet minimum ventilation and air change requirements. Recent advances in UV light-emitting diode (LED) sources have greatly increased the potential applications of UVGI, for example, to inactivate microorganisms in water, liquid, and solid food products (Kebbi et al., 2020). However, accidental overexposure to UV light, in the 254- to 275 nanometer (nm) range, can cause acute eye or skin irritation/damage, so occupants must be shielded from potential exposure.

Risk Matrix and Control Banding Practices

Following the classic industrial hygiene hierarchy of controls (Figure 3), eliminating or controlling exposures to bioaerosols through the use of ventilation and other engineering controls is preferred over either administrative controls or the use of personal protective equipment (PPE). There are occasions, though, when higher level, and thereby more effective, controls are either not available or practicable, cannot completely remove or eliminate the hazard, or when unknown or highly pathogenic bioaerosol exposures are present. In such situations, a combination of engineering, administrative, and use of respiratory and/or other PPE needs to be considered. In deciding appropriate control measures, a decision matrix, which uses the principles of control banding, has been developed (ACGIH, 2021a; Brosseau et al., 2024).

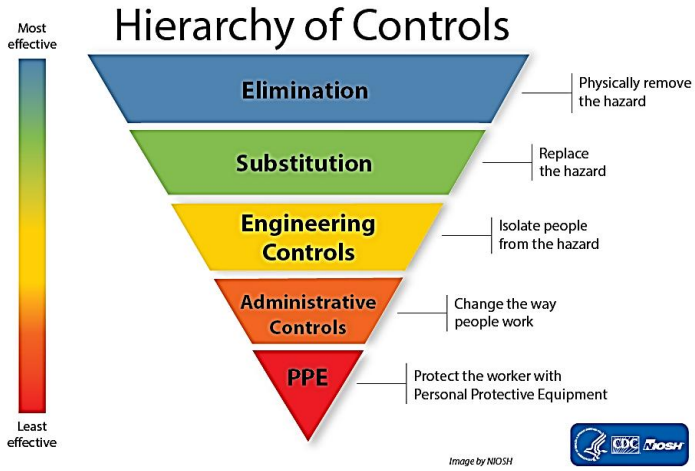

Figure 3 Hierarchy of controls (source: NIOSH, https://www.cdc.gov/niosh/hierarchy-of-controls/about/index.html)

The risk decision matrix is a tool used to assess and prioritize different risks by evaluating their likelihood and the resultant potential impact of each risk. Data for various risks is presented as a chart, which is usually color-coded by severity, with high risks in red, moderate risks in yellow, and low risks in green. The first step in the decision matrix process is to categorize the hazard level of the specific agent, based upon the severity of possible adverse health outcomes and the type of adverse health effects caused by the biological agent. The second step is to categorize the potential for exposure, based upon the anticipated intensity or magnitude of exposure, and the duration and/or frequency of exposures to the specific agent. Then, based on the combination of potential hazard and potential exposure, risk levels can be estimated, and appropriate control actions identified for each level (ACGIH, 2021a).

Selection of respiratory protection for bioaerosols can also be performed using a control banding approach (Brosseau et al., 2024). Control banding, originally developed in the 1990's for the pharmaceutical industry, is a way to create and define

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safety protocols for novel chemicals that have little or no lack toxicologic data, by incorporating data from the known properties of similar compounds (Zalk & Nelson, 2008). Since there are no health-based numerical exposure limits to compare air sample results against for most bioaerosols, the use of respiratory protection factors to determine the adequacy of select respirators to keep exposures below established OELs is limited. Ranking biological agents by risk group, and selecting appropriate respirators protection factors, was proposed by McCullough and Brosseau in 1999, and the essential control banding elements proposed were incorporated in 2018 into Canadian Standard CSA Z94.4-18: Use and Care of Respirators (CSA, 2018).

CONCLUSION

The methods for assessing and controlling exposures to bioaerosols should rely primarily on a thorough and informed visual and olfactory assessment of the building, along with an assessment of occupant symptoms, evaluation of building systems and performance, and application of professional judgement. Air and source sampling of potential environmental sources should only be performed when such testing answers one or more specific questions. As with any other potentially harmful exposure, hazard control selection should follow the classic industrial hygiene hierarchy of controls (i.e., use engineering and administrative controls first, with respiratory and other PPE prescribed only when exposures cannot be adequately controlled or eliminated). By using a layered approach, and incorporating various different methods of controls, the potential for exposures to bioaerosols, and subsequent adverse effects, can be greatly reduced.

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