ASSESSMENT OF BIOAE INDOOR ENV

By Cheryl L. (Cheri) Marcham and John P. (Jack) Springston

BIOAEROSOLS CAN CAUSE a range of potential adverse health issues, including respiratory problems (e.g., asthma exacerbation), allergic reactions and infectious diseases. While the COVID-19 pandemic has made the world more aware of the potential health concerns from exposures to bioaerosols, the term "bioaerosols" represents a much larger category of living and nonliving biological material (ACGIH, 2022). Bioaerosols can consist of fungi, bacteria, spores, pollen, mites, viruses and cell membrane components, and may or may not be viable (ACGIH, 2022). Bioaerosols include airborne compounds, propagules (e.g., seeds, spores, pollen), and fragments arising and derived from biological organisms. They can include fragmented bodies and feces from dust mites, cockroaches and other insects, as well as proteins in saliva, urine and dander from cats, dogs and other furred animals (Flannigan, 2001). Bioaerosols can also include volatile and nonvolatile metabolites and by-products of cells (ACGIH, 2022). Due to metabolic activity or decomposition of nutrients and substrates, many biological agents also potentially contain or release various cellular components (e.g., endotoxins, glucans, chitins), low molecular weight secondary metabolites (e.g., mycotoxins), microbial volatile organic compounds, antigens or allergens (ACGIH, 2022).

The American Conference of Governmental Industrial Hygienists (ACGIH, 2022) uses the term "biological agent" to refer to a substance of biological origin capable of producing an adverse health effect, such as an infection or a hypersensitivity, irritant, inflammatory or other adverse response. Humans are frequently exposed to a wide variety of these contaminants at varying concentrations, usually at very low levels that do not necessarily elicit a response or otherwise result in harm (ACGIH, 2022). While biological agents are ubiquitous in nature, they may be amplified and pose a potential health risk in manmade environments and materials (ACGIH, 2022). How, then, do safety and health professionals assess whether bioaerosols are a concern in an indoor environment and whether control of such bioaerosols is needed?

KEY TAKEAWAYS

- **Bioaerosols are a complex mixture comprised of fungi, bacteria and mites as well as their metabolites and by-products.**
- **Airborne concentrations vary widely, both temporally and spatially.**
- **Assessing and controlling bioaerosols is more complex and difficult than for other chemical and physical hazards faced by safety and health professionals.**
- **Bioaerosol sampling cannot always be used to project possible health effects and should only be conducted by an experienced professional after a thorough informed assessment and when environmental sampling is necessary to answer a particular unanswered question.**

Bioaerosol Hazard & Risk Assessment

Compared to traditional hazard and risk assessments conducted for chemical and physical agents, assessing the hazards and risks associated with 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).

Similar to chemical and physical agents, exposures to bioaerosol agents can occur through various pathways (routes), including inhalation, ingestion, dermal contact and injection. However, hazard and risk assessments for biological agents are complicated by variabilities in both the types and concentrations of bioaerosol agents as well as the individual receptor's susceptibility and response to those agents. Chemical agents, for the most part, have relatively consistent properties, biological responses and subsequent health effects. Unlike these, the biological agent, in many cases, may be a mixture of many biologically derived materials, reflecting the diverse and interactive nature of indoor microenvironments (ACGIH, 2022). For example, indoor sources of microbiological growth and contamination often consist of many genera and species of fungi and environmental bacteria, along with their various components, by-products and metabolites (Flannigan & Miller, 2001).

Like bioaerosols, neither endotoxins nor mycotoxins are a single substance. Endotoxins are a component of the outer cell wall membrane of gram-negative bacteria and can consist of many 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., 2015). In addition, airborne endotoxin levels are generally correlated with other bioaerosol components such as fungi, and the nature of exposures in different occupations are vastly different (Farohki et al., 2018).

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FIGURE 1
SOURCE-PATHWAY-RECEPTOR PARADIGM

Conversely, mycotoxins are nonvolatile, low molecular weight secondary metabolites that are produced by certain fungi under certain conditions. Mycotoxins are capable of causing illness in humans and animals, primarily only after ingestion of large quantities of fungal-contaminated foods. Secondary metabolites and mycotoxins are species-specific and limited to particular strains or chemotypes within species (Bennett & Klich, 2003), but significant quantities of mycotoxins are not produced until water activity reaches 0.95 or greater (Cahagnier et al., 1995; Nielsen, 2003). Note that not all secondary metabolites from fungi are mycotoxins. While roughly 30,000 fungal secondary metabolites had been isolated as of 2010 (Bérdy, 2012), only more than 300 have been identified as mycotoxins as of 2018 (Viegas et al., 2018). Several fungal secondary metabolites are in practical use for human therapy. Examples include the antibiotics penicillin and cephalosporin, and cholesterol-lowering statins (Nielsen & Nielsen, 2017).

In addition to these variabilities in bioaerosol properties that can affect an agent's allergenic or inflammatory potential, transmissibility and infectiousness, the response of the receptor to bioaerosols can also be markedly different depending on receptor health status, sensitivity and a host of other factors. While information about the adverse health effects of some bioaerosol exposures is available from case studies of affected workers, epidemiological studies of groups of workers, and laboratory and clinical evaluations, 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 bioaerosol health-based occupational exposure limits (OELs) extremely challenging.

Airborne concentrations of many bioaerosols, particularly fungi, are highly variable with respect to place and time (Chew et al., 2001; Crawford et al., 2009; Hung et al., 2020; Hyvärinen et al., 2001; Pasanen et al., 1992; Verhoeff et al., 1990). For example, Miller (1992) collected air samples for culturable fungi in a classroom over a 24-hr period and found a significant variability in airborne concentrations over that time. Miller reported that results ranged from multiple data points below detectable levels throughout the day to nearly 1,500 colony forming units per cubic meter (cfu/m^3) in an afternoon sample. Fungal spore concentrations within a damaged building next to Ground Zero following the World Trade Center collapse, collected over a 2-week period in 2002 by the authors, showed similar temporal variability from day to day (Figure 2, p. 26). Given these spatial and temporal variations, and the short duration (e.g., 5 to 10 min) of most bioaerosol sampling methods, occupant exposures over time are difficult to quantify with any accuracy or precision.

All these issues prohibit identifying excessive bioaerosols exposures solely by measuring air concentrations of biological agents. As a result, investigators identify associations between health effects and bioaerosol exposures on a case-by-case basis by combining hazard and risk assessments along with environmental observations and measurements.

Environmental Observations

ACGIH (2022) 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.

However, the mere presence of biological materials on surfaces does not automatically imply contamination. According to published literature from the American Industrial Hygiene Association (AIHA), the presence of some fungal spores and mycelia/hyphal fragments on interior surfaces is typical of normal deposition and is not evidence of fungal colonization (Hung et al., 2005). The Institute of Inspection, Cleaning and Restoration Certification (IICRC, 2015), in its ANSI/IICRC S520-2015, Standard for Professional Mold Remediation, defines a nonimpacted (Condition 1) indoor environment, relative to mold, as

one "that may have settled spores, fungal fragments or traces of actual growth whose identity, location and quantity are reflective of a normal fungal ecology for a similar environment."

Assessing the Environment

When assessing whether bioaerosol contamination is a concern, the steps taken should generally follow the scientific method:

1. identify the problem,
2. gather information,
3. formulate a hypothesis,
4. test the hypothesis, and
5. draw conclusions.

A systematic process to evaluate a hypothesis must be carefully identified and followed. Sometimes, testing a hypothesis involving microbiological growth and contamination requires no more than a thorough, informed visual and olfactory assessment of the environment to come to a reasonable conclusion as to what is occurring. Other times, environmental measurements (e.g., measuring the moisture content of building materials and determining relative humidity levels), along with air and source sampling, may be necessary. However, the sampling plan must be carefully designed to be able to 1. answer the questions being asked, 2. detect and identify the agents expected to be present, and 3. have some verifiable method of understanding and interpreting the data that is generated.

The purpose of a bioaerosol assessment is to identify potential indoor microbial problems, discover the root causes of the problems and note areas that may be susceptible to future problems. A good building assessment will help identify the actions needed to remediate the problem and prevent it from happening again in the future. The building inspection should corroborate any information previously gathered and help in the formulation of any sampling plan. During a preliminary building inspection, an assessor will primarily examine the physical structure of the building (including the building envelope) and look for evidence of water damage or excess moisture, including suspect visible microbial growth. Sources of biological agents may be found in the interior space, outside the building, within crawl spaces, wall cavities or other "hidden" locations inside heating, ventilating and air-conditioning (HVAC) systems, and in other damp areas with conditions conducive for growth. Additionally, the assessor should attempt to identify any pathways and pressure relationships that may connect the contaminant sources to the occupants (receptors).

Clearly, if microbial growth is obvious from visual observations or the presence of musty odors, then there is little doubt that a problem exists. However, in some situations, what appears to be growth is not, so a careful evaluation should be conducted to verify that growth exists. Note that the mere presence of visible microbial growth does not necessarily mean that occupants are exposed to biological agents from that growth, or that health problems occupants may be experiencing are due to the presence of biological agents. To evaluate health risk, investigators must consider the biological agents that may be present and the pathway by which occupants could be exposed to those agents. The investigator should not estimate the likelihood that bioaerosols would be generated or that occupants would inhale the material based solely on observational data, nor should they conclude that likely exposure would be sufficient to cause an adverse health effect or predispose a person to such effects.

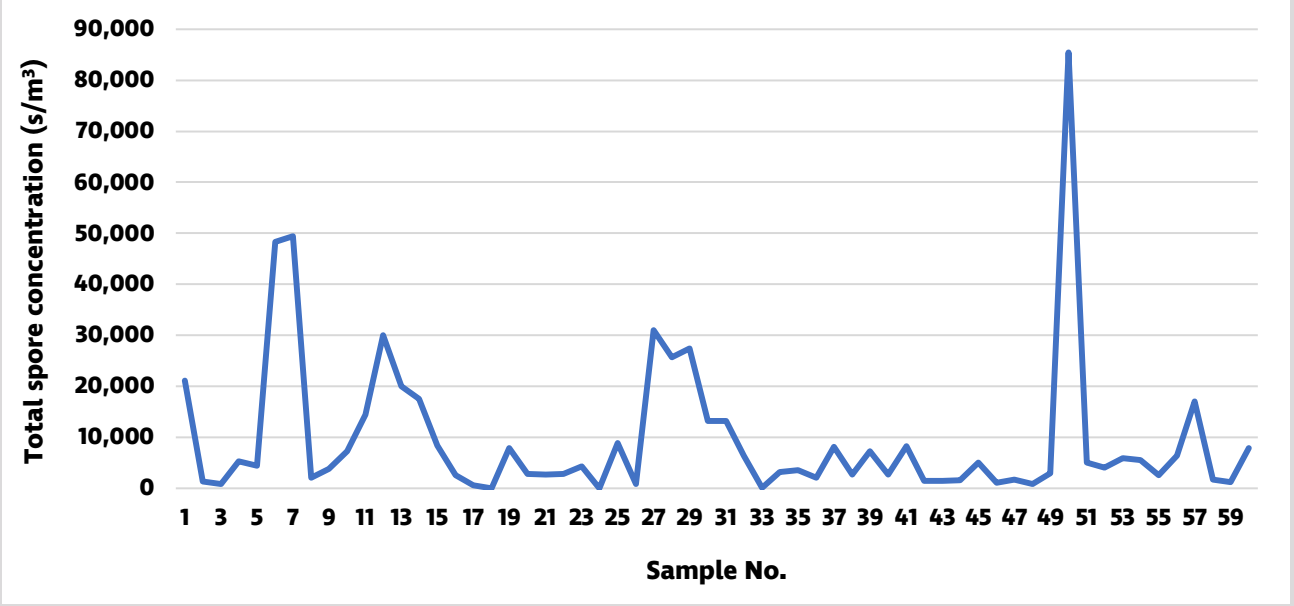
Environmental Sampling

When investigating and evaluating bioaerosols in a building or space, or if microbial growth is suspected to be present on building materials or contents, environmental sampling is

FIGURE 2

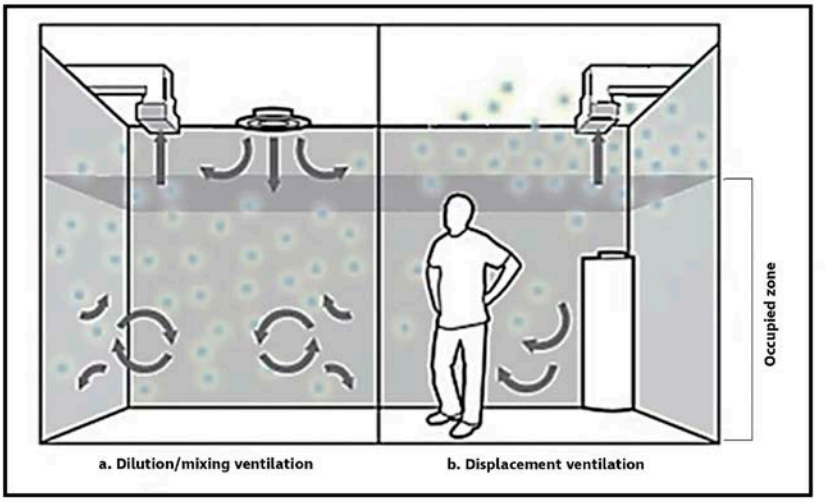
FUNGAL SPORE CONCENTRATION OVER TIME

Fungal spore concentration collected at a building next to Ground Zero in 2002.



Note. t = 15 days

FIGURE 3
DILUTION/MIXING & DISPLACEMENT VENTILATION



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generally unnecessary and, in most cases, not recommended (EPA, 2008; NIOSH, 2012; NYC Health, 2008). This is particularly true for routine assessments or when bioaerosol sampling will not add any additional information to that already documented by a thorough assessment based upon visual inspection in accordance with accepted building assessment standards, such ASTM D7338-14 (ASTM International, 2014). The detailed visual inspection should be carried out by an experienced, qualified and knowledgeable investigator who has the necessary investigative tools to supplement the visual inspection.

Numerous authorities have recommended that microbial growth in occupied interiors, HVAC systems, and on building materials and furnishings (especially if extensive) should be avoided, that uncontrolled microbial growth indoors is unacceptable and should be removed, and that further growth should be prevented (Bailey, 2005; EPA, 2008; Hung et al., 2020; IOM Committee on Damp Indoor Spaces and Health, 2004; Maroni et al., 1995). If visible growth is found, there is often little benefit in performing sampling. Rather, resources should be used for remediation and mitigation of the biological agent's source and reason for its growth and amplification.

The lack of health-based exposure criteria (e.g., threshold limit values or permissible exposure limits) for most types of biological agents precludes bioaerosols sampling and simple comparison of measurements with established air concentrations and dose-response relationships. Sampling may be considered to test suspected sources of biological agents, identify and quantify the agents present, or demonstrate bioaerosol release from environmental and host organism sources, but bioaerosol sampling cannot be used to estimate or project possible health effects. Air sampling should not be relied upon as the sole method to test a hypothesis regarding the source or presence of a bioaerosol. However, bioaerosol sampling can be a useful supplement to a thorough, informed inspection of a space or room that also includes bulk, surface swab or wipe samples from suspect bioaerosols sources.

If sampling is to occur, investigators should have compiled enough information to formulate a hypothesis and determined that environmental sampling is required to answer a particular question. Sampling should only be conducted by professionals with specific experience in designing microbial sampling protocols, the various sampling methods used and interpretation of results (EPA, 2008). A multitude of bioaerosol sampling devices are available on the market, as well as various laboratory analysis methods, so the type of equipment and analysis should be carefully selected to answer the question at hand. Information and guidance on bioaerosol sampling devices is available elsewhere (Springston, 2022).

Before ever taking a sample, the type of sampler to be used must be selected based on the suspected bioaerosol present, the hypothesis about the bioaerosol, and the laboratory's capability to distinguish and identify the bioaerosol of concern. Because OELs to airborne biological agents are not available for comparison, data from individual sampling episodes is often interpreted with respect to baseline data from other environments (e.g., indoors/outdoors or complaint/noncomplaint areas). While investigators often use outdoor air as a baseline measurement against which to compare what is found in indoor air, because of spatial and temporal variability as well as individual measurement uncertainty, an adequate number of samples is essential to make such quantitative comparisons. In addition, interpretation of mixed fungal or bacterial results requires significant knowledge and experience, and proper comparison and interpretation will include assessment of many factors beyond just comparing concentrations. For example, comparing indoor to outdoor bacterial concentrations uses far different criteria than comparing indoor to outdoor mold concentrations.

If microbial samples are collected, utilizing a laboratory that is accredited by the AIHA Environmental Microbiology Laboratory Accreditation Program or the American Association for Laboratory Accreditation is highly recommended. It is also important that field investigators clearly communicate their specific needs and goals regarding sampling to the laboratory personnel with whom they work to best develop an appropriate sampling plan that can provide meaningful results.

Remediation & Control

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 sources of the bioaerosols of concern. Removing the source of the bioaerosols is the best way to eliminate the potential for exposure and any associated risk. For some infectious agents, however, elimination is neither possible nor practical as the source may be the building occupants themselves.

Measures to control microbial colonization and growth on building materials (e.g., moisture control, proper HVAC system maintenance and operation) can reduce the potential number of environmental sources of opportunistic pathogens to which occupants may be exposed. Prompt response to moisture intrusion and other water damage can prevent or limit mold and bacterial growth. Prompt attention to remediating mold contamination once it has been identified can minimize potential occupant exposures to odors, allergens and irritants (EPA, 2012).

Ventilation

If properly designed and implemented, mechanical ventilation can play a critical role in reducing airborne chemical and particulate contaminants, including those that are of biological

FIGURE 4

HAZARD CATEGORIZATION

	Hazard categorization				
	Catastrophic	Critical	Treatable	Marginal	Negligible
Toxic response	4	4	4	2	2
Infection	4	4	3	2	2
Irritation	4	3	2	2	1
Sensitization	4	3	2	1	1
Allergy/Asthma	3	2	2	1	1

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FIGURE 5

EXPOSURE CATEGORIZATION

	Exposure categorization				
	Aggressive disturbance	Active disturbance	Moderate activity	Light activity	No activity
Constant	4	4	4	3	2
Chronic/Interrupted	4	4	3	2	2
Chronic/Episodic	4	3	3	2	1
Occasional	3	3	2	1	1
Acute/Short term	3	2	1	1	1

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FIGURE 6

RISK CATEGORIZATION MATRIX

	Risk level = hazard + exposure			
	Hazard category 4	Hazard category 3	Hazard category 2	Hazard category 1
Exposure category 4	8	7	6	5
Exposure category 3	7	6	5	4
Exposure category 2	6	5	4	3
Exposure category 1	5	4	3	2

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origin. The two types of ventilation that can remove, and thus reduce the concentration of, airborne contaminants are local exhaust ventilation (LEV) and general ventilation. LEV involves the removal of contaminants generated within a space using various designs of capture devices (e.g., fume hoods). This capture takes place as close to the source of the contaminant generation as possible. Examples of LEV in commercial buildings include kitchen range hood exhausts, bathroom exhausts and exhausts on sewage injector pumps. LEV is more frequently used in industrial, laboratory and healthcare settings.

General ventilation can reduce and remove airborne contaminants in one of two distinct airflow arrangements: dilution ventilation and displacement ventilation.

1. Dilution ventilation, sometimes described as mixing ventilation or turbulent flow (Figure 3a, p. 27), is prescribed where the intent is to mix (thus, dilute) contaminated air with "clean" air to lower the concentration of any airborne contaminants within the space to below a given level. With dilution ventilation, conditioned air is supplied at relatively high velocities from air diffusers located at ceiling height, with the return air grilles typically also located at ceiling height. The idea is to supply air in a manner such that the entire room volume is fully mixed, thereby minimizing temperature variations and making contaminant concentrations uniform throughout the space. As noted, 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 air and with as complete air mixing as possible.

2. Displacement ventilation (Figure 3b, p. 27) is generally used when the intent is to keep overall room air mixing to a minimum. With displacement ventilation, conditioned air is supplied at low discharge velocity from air diffusers located at or near floor level, with the return air grilles 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 in as close to a laminar directed flow as is possible, thereby replacing contaminated room air with clean air. Displacement ventilation has been recommended as one of the potentially more effective interventions used in a layered approach to minimizing occupant exposures to highly infectious agents (Bhagat & Linden, 2020; Lipinski et al., 2020).

Air Cleaning Devices

Measures to clean indoor air can help to reduce the concentrations of some bioaerosols and can supplement the benefits of proper ventilation. Standalone air cleaners (e.g., portable HEPA-filtered units) can be used to supplement outdoor air ventilation supplied through HVAC systems to achieve increased air exchange rates (AIHA, 2020; ASHRAE, 2021a; CDC, 2019). However, to be effective, air cleaners must be appropriately sized for optimum particle removal, the rate of air circulation through a unit must be greater than the source emission rate, the device must be capable of delivering a volume of clean air commensurate with the size of the space, and placement of such units must not interfere with existing HVAC systems (ACGIH, 2021). Guidance on determining the appropriate number and size of air cleaning devices, based on room size and clean air delivery ratings (AHAM, 2014), are available from ASHRAE (2021b), CDC (2023), and Lewis and Strode (2021).

Ultraviolet germicidal irradiation technology is also capable of reducing airborne concentrations of infectious agents and other bioaerosols. The germicidal action of ultraviolet (UV) light has been demonstrated, to varying degrees, for viruses, bacteria and fungi, with some biological agents being more resistant than others (Kowalski, 2009). However, accidental overexposure to UV light in the 254 to 275 nanometer range can cause acute eye or skin irritation/damage, so occupants must be shielded from potential exposure. UV lights can be installed inside occupied rooms on the upper section of walls (upper room) and inside HVAC systems. Good vertical air mixing is required to bring bioaerosols present in a room in contact with the upper room ultraviolet germicidal irradiation source for effective use (First et al., 1999). For in-duct applications, a balance between duct size, ventilation flow rate and residence time in the UV light zone must be achieved to allow sufficient contact time for inactivation, while also allowing sufficient supply volume for meeting minimum air change requirements.

Risk Matrix & Control Banding Practices

Following the classic industrial hygiene hierarchy of controls, eliminating or controlling exposures to bioaerosols through engineering controls such as ventilation is preferred over administrative controls or PPE use. However, there are occasions where higher level controls are not available or not feasible, cannot completely remove the potential hazard, or unknown or highly pathogenic bioaerosol exposures are present. In such situations, a combination of engineering, administrative, and respiratory controls and other PPE should be considered. To help determine appropriate control measures, ACGIH has developed a decision matrix that uses the principles of control banding (ACGIH, 2021; NIOSH, 2023).

The first step in the decision matrix process is to categorize the specific agent's hazard level based upon the severity of possible adverse health outcomes and the type of adverse health effects caused by the biological agent (Figure 4). The second step is to categorize the potential for exposure, based upon the anticipated intensity or magnitude of exposure, and the duration or frequency of exposures to the specific agent (Figure 5). Then, based on the combination of potential hazard and potential for exposure, risk levels (bands) can be estimated, and appropriate control actions are provided for each risk level or band (Figure 6; ACGIH, 2021).

Selection of respiratory protection for bioaerosols can also be performed using a control banding approach. Since no numerical health-based exposure limits exist for interpreting air sampling results for most bioaerosols, the traditional use of respiratory protection factors to reduce exposure below established OELs is limited. Ranking biological agents and selecting appropriate respirators protection factors was proposed by McCullough and Brosseau in 1999. The essential control banding elements proposed by McCullough and Brosseau were incorporated into the Canadian standard CAN/CSA Z94.4-18, Selection, Use and Care of Respirators (CSA, 2018).

Conclusion

The methods for assessing and controlling exposures to bioaerosols should rely on visually inspecting buildings, assessing occupant symptoms, evaluating building performance, testing potential environmental sources only where appropriate, and applying professional judgment. As with any other potentially hazardous exposure, control selection should follow the classic industrial hygiene hierarchy of controls (i.e., using engineering and administrative controls first, with respiratory and other PPE prescribed only when exposure cannot be adequately controlled or eliminated). By using a layered approach and incorporating various methods of controls, the potential for risk reduction to bioaerosols can be greatly improved. **PSJ**

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Cheryl L. (Cheri) Marcham, Ph.D., CSP, CIH, CHMM, FAIHA, is an associate professor and program coordinator for the M.S. in Occupational Safety Management program at Embry-Riddle Aeronautical University. She has served on the board of directors of the American Industrial Hygiene Association, BCSP and the Board for Global EHS Credentialing. She is vice chair and has served as chair of the American Conference of Governmental Industrial Hygienists (ACGIH) Bioaerosols Committee and is coeditor of the forthcoming update to the ACGIH publication, ***Bioaerosols: Assessment and Control***. Marcham is a professional member of ASSP's Oklahoma City Chapter.

John P. (Jack) Springston, M.S., CSP, CIH, FAIHA, is industrial hygiene services manager, branch safety officer, and training director for Atlas Technical in New York City and Long Island. He has been an industrial hygiene and occupational safety consultant for more than 35 years. He holds an M.S. in Environmental and Occupational Health Sciences from Hunter College and a B.S. in Environmental Biology from Southampton College. He is chair of the ACGIH Bioaerosols Committee, and is coeditor of the forthcoming update to the ACGIH publication, ***Bioaerosols: Assessment and Control***. Springston is a professional member of ASSP's Long Island Chapter.

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