Particuology xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Particuology

journal homepage: www.elsevier.com/locate/partic

Six-day measurement of size-resolved indoor fluorescent bioaerosols of outdoor origin in an office

Yangyang Xie[a,1], Oscar A. Fajardo[c,1], Weizhuo Yan[c], Bin Zhao[a,b,*], Jingkun Jiang[c,d,**]

[a] Department of Building Science, School of Architecture, Tsinghua University, Beijing 100084, China
[b] Beijing Key Laboratory of Indoor Air Quality Evaluation and Control, Tsinghua University, Beijing 100084, China
[c] State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Tsinghua University, Beijing 100084, China
[d] State Environmental Protection Key Laboratory of Sources and Control of Air Pollution Complex, Beijing 100084, China

ARTICLE INFO

Article history:
Received 10 March 2016
Received in revised form 29 August 2016
Accepted 18 September 2016
Available online xxx

Keywords:
Fluorescent bioaerosols
Indoor air
Outdoor air
Waveband integrated bioaerosol sensor (WIBS)
Particle size distributions
Concentrations

ABSTRACT

Indoor airborne bioaerosols of outdoor origin play an important role in determining the exposure of humans to bioaerosols because people spend most of their time indoors. However, there are few studies focusing on indoor bioaerosols originating from outdoors. In this study, indoor versus outdoor size-resolved concentrations and particle asymmetry factors of airborne fluorescent bioaerosols in an office room were measured continuously for 6 days (144 h) using a fluorescent bioaerosol detector. The windows and door of this room were closed to ensure that there was only air infiltration; moreover, any human activities were ceased during sampling to inhibit effects of indoor sources. We focused on fine particles, since few coarse particles enter indoor environments, when windows and doors are closed. Both indoor and outdoor fluorescent bioaerosol size distributions were fit with two-mode lognormal distributions (indoor $R^2 = 0.935$, outdoor $R^2 = 0.938$). Asymmetry factor distributions were also fit with lognormal distributions (indoor $R^2 = 0.992$, outdoor $R^2 = 0.992$). Correlations between indoor and outdoor fluorescent bioaerosol concentrations show significant concentration-attenuation and a time lag during the study period. A two-parameter, semi-empirical model was used to predict concentrations of indoor fluorescent bioaerosols of outdoor origin. The measured and predicted concentrations had a linear relationship for the studied size fractions, with an R^2 for all size fractions of larger than 0.83.

Introduction

Exposure to bioaerosols can cause atopic diseases and other adverse health effects, such as asthma, allergenic, toxigenic, rheumatic, and infectious diseases (Burger, 1990; Chen, Zhao, & Weschler, 2012; Hanski et al., 2012; Menetrez, Foarde, & Ensor, 2001). Currently, people spend more than 80% of their time indoors (Brauer et al., 2000; Klepeis et al., 2001; Wu, Xu, Shi, & Zhao, 2014). It is widely recognized that bioaerosols play a significant role in indoor air pollution (Jo & Seo, 2005; Nazaroff, 2016). Some studies assessed indoor fungal, bacterial, and other bioaerosol concentrations and their size distributions in residential and office premises (Green, Scarpino, & Gibbs, 2003; Górny, Dutkiewicz, & Krysinska-Traczyk, 1999; Kalogerakis et al., 2005). Other studies focused on patterns of indoor bioaerosol generation, such as the effects of human activities and other emissions on exposure to bioaerosols (Bhangar et al., 2016; Bhangar, Huffman, & Nazaroff, 2014; Brandl, von Däniken, Hitz, & Krebs, 2008; Chen & Hildemann, 2009a; Grice & Segre, 2012). However, there are very few studies focusing on indoor bioaerosols that are generated outdoors.

Several studies (Bowers et al., 2013; Gabey et al., 2010; Toprak & Schnaiter, 2013) have shown that bioaerosols play an important role in the near-surface atmosphere. This may be more important in those countries and regions experiencing severe atmospheric pollution (Xie, Zhao, Zhang, & Luo, 2015). For instance, Cao et al. (2014) have shown that the concentrations of some outdoor inhalable pathogens are higher on hazy days in Beijing. Because people spend most of their time indoors, it is important to understand how much outdoor bioaerosols contribute to indoor environ-

* Corresponding author at: Department of Building Science, School of Architecture, Tsinghua University, Beijing 100084, China. Fax: +86 10 62773461.
** Corresponding author at: State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Tsinghua University, Beijing 100084, China. Fax: +86 10 62773597.
E-mail addresses: binzhao@mail.tsinghua.edu.cn (B. Zhao), jiangjk@tsinghua.edu.cn (J. Jiang).
[1] These authors contributed equally to this work.

http://dx.doi.org/10.1016/j.partic.2016.09.004
1674-2001/

Nomenclature

a	The air change rate in the room (h^{-1})
A	The range of the fit curve
A_0	The range of the first mode
A_1	The range of the second mode
$C_{i,in}$	The number concentration of indoor aerosols in the ith size range (#/L)
$C_{i,out}$	The number concentration of outdoor aerosols in the ith size range (#/L)
C_{in}^{Me}	The number concentration of the measurement (#/L)
$C_{i,in}^{Me}$	The number concentration of the measurement in the ith size range (#/L)
C_{in}^{Pr}	The number concentration of the model prediction (#/L)
$C_{i,in}^{Pr}$	The number concentration of the model prediction in the ith size range (#/L)
$\bar{E}$	Mean background signal
E_i	The intensity measured by the ith quadrant
$E_{Threshold}$	The noise threshold
$\dot{G}$	The emission rate (#/s)
k	The instrument-defined constant
K_i	The deposition rate in the ith size range (h^{-1})
$\log d_p$	The logarithmic size distribution function (μm)
N_{FL1}	The fluorescent aerosol particles in channel 1 (#)
P_i	The penetration ratio in the ith size range
P	The penetration ratio
$\dot{R}$	The resuspension rate (#/s)
V	The volume of the room (L)
Y	The height of the fit curve
Y_0	The height of the first mode
Y_1	The height of the second mode
π	Ratio of the circumference of a circle to its diameter
σ	The standard deviation
σ_0	The standard deviation of the first mode
σ_1	The standard deviation of the second mode
μ	The mathematical expectation
μ_0	The mathematical expectation of the first mode
μ_1	The mathematical expectation of the second mode
ϕ	The characteristic parameter of the outdoor influx (h^{-1})
ϕ_i	The characteristic parameter of the outdoor influx in the ith size range (h^{-1})
$\phi_{i,b}$	The optimal ϕ_i in the search range of the ith size range (h^{-1})
φ	The characteristic parameter of the indoor sinks (h^{-1})
φ_i	The characteristic parameter of the indoor sinks in the ith size range (h^{-1})
$\varphi_{i,b}$	The best φ_i in the search range of the ith size range (h^{-1})
τ	The age of the air (h)

ments. There have been several previous studies of the relationship between indoor and outdoor bioaerosols in various indoor environments around the world. For example, Chen and Hildemann (2009b) compared the size-resolved concentrations of particulate matter and bioaerosols in indoor and outdoor environments of homes. Shelton, Kirkland, Flanders, and Morris (2002) profiled airborne fungi in buildings and outdoor environments in the United States. Lee et al. (2006) studied the relationship between indoor and outdoor bioaerosol samples collected with a button inhalable aerosol sampler in urban homes. However, because these studies did not control indoor emissions, they could not quantify the contribution of outdoor aerosols to indoor environments. Furthermore, the concentrations and asymmetry factors (AFs) for various size ranges of bioaerosols were not measured in these studies, because of the limitations of their measurement technology.

Various measurement methods, such as culturing to calculate colony forming units per cubic meter of air and microscopic examination, flow cytometric analysis of air samples, polymerase chain reactions, adenosine triphosphate bioluminescence, bioaerosol mass spectrometry, micro-Raman spectroscopy, DNA- or RNA-based methods, and fluorescence spectrometry (Górny et al., 1999; Lax et al., 2014; Mandal & Brandl, 2011; Robinson et al., 2013; Rosch et al., 2005), have been used to characterize bioaerosols. Despite the reliability of these methods, they are often carried out as off-line analyses, following bioaerosol collection. In contrast, other technologies, such as light-induced fluorescence or ultraviolet-light-induced fluorescence (UV-LIF), can offer a near-instantaneous distinction between fluorescent bioaerosol and other aerosol particles, without the need for staining or incubating samples. The evaluation of bioaerosol populations using fluorescence-based spectrometers has been carried out in urban, suburban, and desert environments in the United States (Pan, Pinnick, Hill, Rosen, & Chang, 2007), classroom emissions (Bhangar et al., 2016), and tropical forest emissions (Gabey et al., 2010), as well as settings in Manchester (UK), Mainz (Germany) (Huffman, Treutlein, & Pöschl, 2010), Puy du Dome (France) (Gabey et al., 2013), and Karlsruhe (Germany) (Toprak & Schnaiter, 2013).

In the present study, indoor fluorescent bioaerosols in an office located on a university campus and the corresponding outdoor fluorescent bioaerosol population were measured continuously over 6 days (144 h) to determine the contribution of outdoor fluorescent bioaerosols to indoor fluorescent bioaerosols. A waveband integrated bioaerosol sensor version 4A (WIBS-4A), which can measure fluorescent bioaerosols with high-temporal and particle-size resolution, was employed. Few studies that have used an in-situ method to assess the infiltration of outdoor fluorescent bioaerosols into indoor environments. Indoor emissions were strictly controlled to ensure that bioaerosols originated entirely from outdoors. Thus, an infiltration factor could be obtained by quantifying the contribution of outdoor fluorescent bioaerosols. A model to predict the indoor fluorescent bioaerosol concentration of outdoor origin was developed based on the measured particle size distributions and concentrations of indoor versus outdoor fluorescent primary biological aerosol particles (FBAPs).

Materials and methods

Experimental method

Design of the measurements

Indoor aerosol measurements were undertaken in an office, located on the second floor of the Environmental Science building on the campus of Tsinghua University, Beijing, China. The room was unoccupied and no activities were carried out inside the room while sampling. Thus, all indoor sources were precluded, aside from any ongoing impact related to the initial installation of the sampling equipment. The wind speed was lower than 0.5 m/s indoors and the air exchange only occurred through window cracks. There is no heating, ventilation or air-conditioning system in this office; it also has no furniture and no visible signs of dampness. The office has a cement floor with an area of $5.1 \times 2.7\ m^2$ and is 2.8 m high. There are two casement windows made of aluminum alloy and glass; one window faces towards the outdoors ($1.4 \times 1.4\ m^2$), the other one faces an inner corridor ($0.8\ m \times 1.3\ m^2$). There is one door ($1.9 \times 0.85\ m^2$). Once the instruments were installed, the door

Please cite this article in press as: Xie, Y., et al. Six-day measurement of size-resolved indoor fluorescent bioaerosols of outdoor origin in an office. *Particuology* (2016), http://dx.doi.org/10.1016/j.partic.2016.09.004