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Journal of Aerosol Science 119 (2018) 91–96

Contents lists available at ScienceDirect

Journal of Aerosol Science

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

Reprint of bioaerosol: A bridge and opportunity for many scientific research fields

ARTICLE INFO

Keywords:
Bioaerosol
PBAP
Xiangshan Science Conference
Special issue
Sampling
Detection

ABSTRACT

Bioaerosol is a concept that is used to describe all biological materials suspended in the air, including bacteria, fungi, viruses, pollen, and their derivatives such as allergens, endotoxin, mycotoxins and etc. In some studies, primary biological aerosol particle (PBAP) is also coined to refer to intact microbes in the air. Bioaerosol is a multidisciplinary research subject, involving many different fields such as microbiology, mechanical engineering, air pollution, medical science, epidemiology, immunological science, biochemistry, physics, nanotechnologies and etc. The bioaerosol field has undergone about 200 years' research history since 1833 when mold spores were first detected in the air by Charles Darwin on the Cape Verde Islands. In recent decades, there has been a research boom in bioaerosol field, thus triggering many outstanding research opportunities. Visible progress has already been made in understanding bioaerosol roles in human health, atmospheric and ecological impacts as well as their respective technologies: bioaerosol capture, monitoring and also inactivation. Most recently, researchers from different fields start to bridge together for solving bioaerosol challenges and addressing key scientific problems, e.g., bioaerosol spread, real-time detection, indoor microbes, human bioaerosol emissions, and bio-defense. Toward this effort, a "Bioaerosol Xiangshan Science Conference-the 600th" has been successfully held in the summer in Beijing, China. A total of 47 scientists and funding agency officials including leading bioaerosol experts from overseas were invited and two-day long extensive discussions on bioaerosol progress and problems were carried out. Future bioaerosol directions have been outlined by the attendees during the conference. Some of the participants have also contributed to this bioaerosol special issue. This special issue consists of a total of 20 bioaerosol articles from eight countries including one review, and contributes to the advances in bioaerosol emission, transmission, health effects, ambient bioaerosols, method development and instrumentation, and control. Through this special issue, the bioaerosol community has obtained a better understanding of bioaerosol health risks and developed the corresponding strategies to confront the threats. This special issue might serve as a starting point to not only link bioaerosol scientists from different continents, but also bring together people from various fields yet with an interest in bioaerosol to collectively advance the field further.

1. Bioaerosol sources, transport and impacts

Bioaerosol collectively refers to all suspended particles of biological origins in the air. In theory, all biological materials can be released either directly or resuspension into the air upon various disturbances from the earth surfaces such as soils, oceans, animals, forests, humans and etc. Once airborne, as shown in Fig. 1 biaoerosol particles could undergo human inhalation, dry/wet depositions, aerial transport, ice nucleation, cloud condensation processes, atmospheric transformation and others. Accordingly, they have important impacts on infectious disease spread, allergic diseases, bio-security, atmospheric chemistry as well as climate (Douwes et al.,

DOI of original article: http://dx.doi.org/10.1016/j.jaerosci.2017.07.010

https://doi.org/10.1016/j.jaerosci.2018.01.009

Available online 02 March 2018
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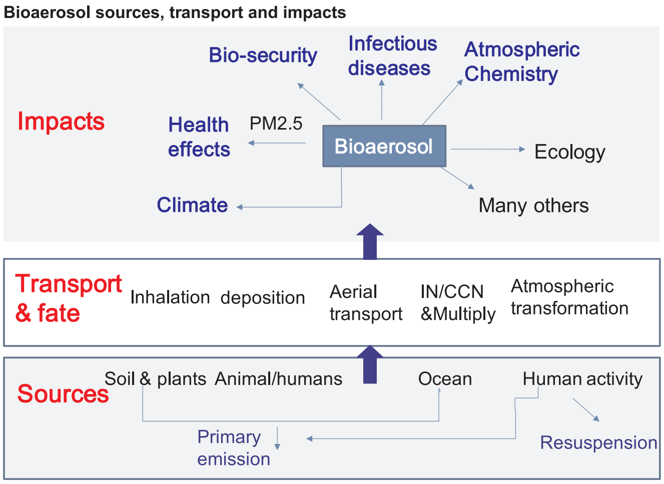

Fig. 1. Bioaerosol emission sources including primary and resuspension, transport & fate, IN/CCN, transformation and impacts.

2003; Nazaroff, 2016; Després et al., 2012; Xu et al., 2011; Dannemiller, Gent, Leaderer, & Peccia, 2016). According to World Health Organization (2016), lower respiratory infection is ranked as the 4rd killer of humans, among which children under the age of 5 is suffering significant loss of life. The evidence for bioaerosol related adverse health effects is accumulating and recognized by worldwide bioaerosol scientists, and this can be exemplified by the citations (> 800) of the review by Douwes, Thorne, Pearce, and Heederik (2003). In addition, the health threats from bioaerosol exposure can be also greatly enhanced by airborne transmission of infectious agents via breathing such as SARS in 2003 and H1N1 in 2009 and also the potential risks of biological agent attacks, e.g., the anthrax events in 2001 in the United States. In term with allergic diseases, a study by Shiraiwa et al. (2012) reports that allergenic potency of allergens can be significantly increased by the nitrification in polluted air, possibly explaining the increasing prevalence of allergy in urban cities. On another front, increasing number of studies show that bioaerosol particles could have played important roles in the atmospheric chemistry as oxidants/reducer and climate as ice nucleator (IN) and cloud condensation nuclei (CCN);and specific discussions can be found in the review by Després et al (2012) and Haddrell and Thomas (2017). In a recent work, it was shown that different geographic locations with varying climate conditions have distinctive fluorescent bioaerosol particle size distribution and concentration levels, which reflects or influences local ecological and microbial landscape (Wei et al., 2015) and such similar findings were also observed in the United States (Perring et al., 2015). In a recent review by Haddrell and Thomas (2017), it was pointed out that in next 10 years multidisciplinary approaches combining existing and novel techniques in atmospheric chemistry, aerobiology and molecular biology will merge to help understand the long-sought mechanisms of bioaerosol transport and decay. In addition to these impacts, some other studies are also emerging such as use of bioaerosols as forensic fingerprints (Castillo, Staton, Taylor, Herckes, & Hayes, 2012) and bioaerosol emissions from humans via breathing or skin (Hospodsky et al., 2012; Xu, Wu, & Yao, 2017; Yamamoto, Hospodsky, Dannemiller, Nazaroff, & Peccia, 2015). During the summer of 2017, the 600th "Xiangshan Science Conference (2017)" with a bioaerosol focus has been successfully held in Beijing, China. A total of 47 scientists and funding agency officials including leading bioaerosol experts from overseas were invited and two-day long extensive discussions on bioaerosol progress and problems were carried out. Future bioaerosol directions have been outlined by the attendees during the conference. In the 600th Xiangshan Science Conference, participants also discussed the potential beneficial roles of bioaerosol on human's health such as the hygiene hypothesis. Nonetheless, biological fraction of particulate matter is often neglected in many health related studies, which could be partially due to limited established dose-response relationship for bioaerosol (Eduard, Heederik, Duchaine, & Green, 2012).

2. Bioaerosol sampling, detection and inactivation

In general, bioaerosol sampling is the first step toward characterizing bioaerosol exposure risks. For human health, indoor bioaerosols are more relevant, which are largely originated from human emissions, floor resuspension and some direct emissions such as fungal spore emissions (Qian, Peccia, & Ferro, 2014; Yamamoto et al., 2015). During the 600th Xiangshan Science Conference, majority of the participants agreed that airborne transmission of infectious agents was responsible for the larger outbreaks of infectious disease spreads. During the conference, the participants also outlined several challenges for bioaerosol sampling as shown in Fig. 2, e.g., low quantity and small size and also loss of viability and identification property during the collection process. Among others, electrostatic sampling and wetted cyclones are attracting great attention (Yao and Mainelis, 2006; Han, Nazarenko, Lioy, & Mainelis, 2011; McFarland et al., 2010). Previously, it was discussed that high volume aerosol-to-hydrosol sampling is greatly needed in order to concentrate bioaerosol agents into small amount of liquids (Xu et al., 2011). It was concluded that specific sampler should be selected for a particular species of interest, and no standardized sampling protocol can be generalized in other studies (Haddrell & Thomas, 2017; Haig, Mackay, Walker, & Williams, 2016). Overall, the sampling has to be adjusted accordingly for different purposes of the studies. With the development of metagenomics, bioaerosol researchers are now able to analyze thousands of microorganisms

Fig. 2. Group photo of the attendees during the 600th Xiangshan Science Conference with a bioaerosol focus held in Beijing on June 29–30, 2017 (Photo credit by Xiangshan Conference Office).

offline in the air. However, one study pointed out that it is still challenging to study viral aerosols using the technique due to limited quantity of viruses in the air samples (Prussin, Marr, & Bibby, 2014). In terms of real-time detection, it is commonly agreed that it is rather difficult if it is not impossible to achieve real-time detection to the species level. Current methods such as culturing and DNA based method are time consuming, while fluorescence-based detection methods such as UV-APS or WIBS fail to identify bioaerosol particles to the species levels in addition to interferences from fluorescent chemicals (Després et al., 2011). In a previous work, real-time detection of airborne influenza viruses such as H3N2 has been successfully demonstrated by integrating air sampling, microfluidics and silicon nanowire sensing (Shen et al., 2011; Xu et al., 2011), and the same technology was also used for detecting influenza viruses in the exhaled breath (Shen et al., 2012). However, given current available technologies, it is impossible to real-time monitor all the airborne biological agents to the species level unless there will be a breakthrough in analytical field in the distant future. The ultimate goal of bioaerosol detection is able to protect people from the bioaerosol exposure in time. Over the past years, many different approaches have been investigated in inactivating environmental bioaerosols, including thermal treatment, microwave irradiation, ion emission, atmospheric cold plasma, nano-particle assisted fiber as well as ventilation (Ghosh, Lal, & Srivastava, 2015; Xu et al., 2011). However, with respect to personal protection most people often choose to wear a respirator especially during a flu season (Zou and Yao, 2015). (Fig. 3)

3. Bioaerosol special issue

To further tackle emerging and unresolved problems, a “Bioaerosol” special issue has been approved by the editorial board of the Journal of Aerosol Science during the European Aerosol Conference held in Tours, France in 2016. Particularly, this special issue was targeted to focus on the following topics: 1) virus and endotoxin sampling, portable high volume sampler, bacteria detection, and

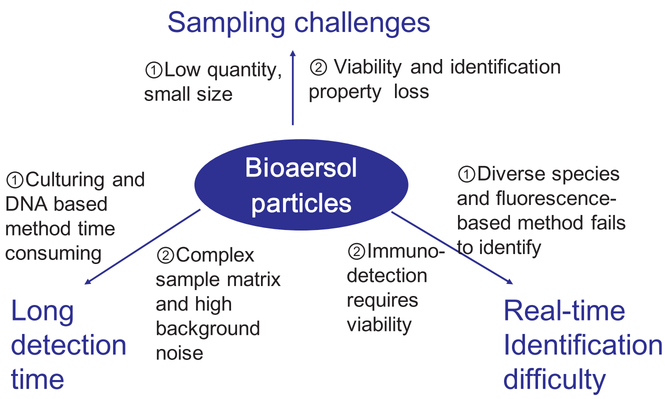

Fig. 3. Key bioaerosol challenges outlined during the 600th Xiangshan Science Conference held in Beijing.

nosocomial viral aerosol infection control; 2) inhaled and exhaled bioaerosols, and their potential diagnosis application and environmental consequences; respiratory pathogen detection and survival as well as method and instrumentation developments; 3) bioaerosol emission and aerosol related transmission of infectious diseases including those animal-borne ones; 4) ambient bioaerosols as well as their monitoring in poultry and health effects; 5) bioaerosol control technologies including bio-defense. This special issue consists a total of 20 bioaerosol articles from eight countries including one review, and contributes to the advances in bioaerosol emission, transmission, health effects, ambient bioaerosols, method development and instrumentation, and control. This special issue might serve as a starting point to not only link bioaerosol scientists from different continents, but also bring together people from various fields yet with an interest in bioaerosol. Leading bioaerosol experts around the world have been invited to submit their papers, and those accepted papers are set to appear both in a regular issue and also a virtual special issue (https://www.sciencedirect.com/science/journal/00218502/vsi).

With respect to bioaerosol emissions, Zheng, Chen, Yao, and Li (2018) utilized a new protocol (combing exhaled breath collection with Loop Mediated Isothermal Amplification (LAMP) and detected *Haemophilus influenzae*, *Pseudomonas aeruginosa*, *Escherichia coli*, *Staphylococcus aureus* and Methicillin-resistant Stphylococcus aureus (MRSA) in exhaled breath. Among these pathogens, *H. influenzae* was found to be the leading cause for the respiratory bacterial infections (Zheng et al., 2018). Their study also suggests that human exhaled breath might be an important bacterial pathogen emission source. Xu et al. (2017) have shown that exhaled breath alone might account for about 17% of the total bioaerosol emissions from humans. In another study, an aerosol droplet sampling technique was developed to collect pulmonary surfactant from alveolar lining fluid (ALF), and the developed method can be used to assess lung functions (Mizev, Shmyrova, & Mizeva, 2018). These two studies indicate that breathing is an important source of bioaerosols, and they could be potentially useful for disease diagnostics. In another work, computational fluid dynamics (CFD) method was applied to studying exhaled droplet dispersion; and found that ambient relative humidity plays an important role on the droplet dispersion and majority of the droplets reach within ± 0.5 m of the person's mouth before they become droplet nuclei or fall onto the ground (Ji, Qian, Ye, & Zheng, 2018). Ambient bioaerosols have many different emission sources, including humans as discussed here. Scientists from Canada found that certain species such as *Actinobacteria* could be preferentially released into the air due to their dry surface characteristics, e.g., from the compost facility (Veillette et al., 2018). Wu et al. (2018), on the other hand, found that virulence factor genes in *E. coli* in animal houses can be emitted into the air, and further transmitted to the outside, implying a significant public health challenge from zoonosis. Górny, Gołofit-Szymczak, Cyprowski, Stobnicka, and Ławniczek-Wałczyk (2018) suggest that microbial transport could be facilitated by fibers that are encountered in natural environments, but with influences from microbial charges. Pyankov, Bodnev, Pyankova, and Agranovski (2018) studied the survival of airborne Middle East Respiratory Syndrome (MERS-CoV) virus and found that their survival depended on the temperature and humidity. Particularly, in this special issue Yuan, Zhang, Leung, Cowling, and Yang (2018) have reviewed viral aerosol transmission and infections as well as their controls in hospital settings.

To identify these airborne biological agents, as discussed above, an important step is the sampling. In this special issue, a number of sampling technologies have been developed including exhaled breath collection, endotoxin, bacteria and virus sampling, and portable high volume sampling (Mizev et al., 2018; Zheng et al., 2018; Chen et al., 2018; Kim, Park, Kim, Yong, & Hwang, 2018; Li et al., 2018; Duquenne, Coulais, Bau, & Simon, 2018). A new collection device called BioScreen was shown to be able to obtain 300–500 μL EBC within 3–5 min (Zheng et al., 2018). Li et al. (2018) compared three different virus sampling methods, e.g., liquid sampler BIoSampler (SKC), gelatin filter and a glass fiber filter, and they found that the highest viral collection efficiencies for the SKC BioSampler and gelatin filter were 5% and 1.5%, respectively; and the SKC BioSampler was detected to perform best among the methods tested. For biological derivatives, a NIOSH BC-112 cyclone was found to be suitable for the measurement of airborne endotoxins (Duquenne et al., 2018). Air sampling, e.g., use of an impactor, often causes damages to the culturability of airborne microbes. To overcome this problem, Kim et al. (2018) developed a lab-made electrostatic rod-type sampler and showed that those micrograms such as *S. aureus* collected using the developed rod-type electrostatic sampler had much less morphological damages than those collected from a single stage Andersen type impactor. Nonetheless, in some cases airborne pathogens could be in very low counts, and a high volume sampler is needed especially in some urgent situations. In this special issue, Chen et al (2018) have designed and developed a battery-powered high volume sampler (HighBioTrap) which was shown to have a cutoff size of 2 μm, collecting 1 m^3 air per minute. The HighBioTrap sampler was shown to recover more bacterial aerosol species per min than the BioStage impactor, and the sampler could be especially useful in rapid qualitative microbial analysis. All these sampling strategies developed can assist in efficiently identifying the hidden airborne biological hazards.

It is known that air is a receptor for many pollutants emitted from the ground. Any biologicals from the ground, e.g., soils, humans, forests, river and many human activities, could be to some extent released into the air. As an effort of understanding ambient bioaerosols, Emygdio, Degobbi, Gonçalves, and Andrade (2018) reported fungal spore concentration levels in Brazil and found the highest concentration up to 23,780 spores/m^3 in autumn and typically the concentration was found to be the highest at the dawn. On the other hand, Lin et al. (2018) showed that the spore concentration levels depended the urbanization, and they also found that urban and rural areas had significantly different airborne fungal floras and spore concentration. Recently, there is an increased interests in studying bioaerosol dynamics during the haze events (Wei et al., 2016). Here, Xie et al. (2018) studied the culturable bacterial aerosol dynamics under different air pollutions levels, and they found that the concentration levels varied greatly with season and microbial levels were not always increasing during the haze days. As an important bacterial membrane component, endotoxin exposure has attracted great attention with respect to health. In this special issue, researchers have studied endotoxin levels in a typical university campus and evaluated the exposure risks (Liu, Zhang, Li, Liu & Sui, 2018). They have indicated that children presented the highest exposure risk of airborne endotoxin. In addition to traditional detection methods, some studies in this special issue reported the developments of new bioaerosol detection methods such as use of LAMP together with microfluidics and

DNA stain together with UV-APS (fluorescence-based bioaerosols sensor) (Liu et al., 2018; Nasrabadi, An, Kwon, & Hwang, 2018; Zheng et al., 2018). Liu, Zhang, Wen, and Wang (2018) reported a bioaerosol detection system that combines sampling, transport, DNA extraction and also LAMP-based detection, while Nasrabadi et al. (2018) reported a new method of differentiating alive and dead bioaerosol particles using fluorescence-based method. All these new developments have helped the researcher obtain a better understanding of bioaerosols in the atmosphere and also help protect people from the hidden biological threats.

In addition to bioaerosol emission, transmission, detection, this special issue also consisted three control studies including one review for viral aerosol control in hospital environments. Lu, Hsu, Huang, Liang, and Huang (2018) studied the performances of airborne disinfectants such as chlorine dioxide and weak acid hypochlorous water on bioaerosol levels in a university library, and found the disinfectants can be used to reduce the bioaerosol levels that comply with the regulations. For hospital environments, Yuan et al. (2018) pointed out that cross infections through aerosol routes still occur despite of controlling efforts such as engineering solutions, hand hygiene and wearing face masks. The 2017–2018 winter occurrence of large number of flu infections both in China and the world further necessitates the viral aerosol transmission and exposure control. In some rare situations, some bio warfare agents could be intentionally or accidentally released into the human environments. Here, one study investigated the possibility of using iodine-bearing reactive materials for inactivating airborne spores such as anthrax, and they discussed the relevant mechanisms and influencing factors on the inactivation (Wang, Schoenitz, Grinshpun, Yermakov, & Dreizin, 2018). Despite of many efforts in airborne pathogen control, lower respiratory infections still remain to be one of the major killer for humans worldwide.

4. Concluding remarks

Bioaerosol is a multidisciplinary research subject, involving many different fields such as microbiology, mechanical engineering, air pollution, medical science, epidemiology, immunological science, biochemistry, physics, nanotechnologies and etc. There will be about 200 years' research history for the bioaerosol field since 1833 when mold spores were first detected in the air by Charles Darwin on the Cape Verde Islands. In recent decades, there has been a research boom in bioaerosol field, which thus triggers many outstanding research opportunities. Visible progress has already been made in understanding bioaerosol roles in human health, atmospheric and ecological impacts as well as their respective technologies: bioaerosol capture, monitoring and also inactivation. Most recently, researchers from different fields start to bridge together for solving bioaerosol challenges and addressing key scientific problems, e.g., bioaerosol spread, real-time detection, indoor microbes, human bioaerosol emissions, and bio-defense. Toward this effort, a “Bioaerosol Xiangshan Science Conference-the 600th ” has been successfully held in the summer in Beijing, China. As a part of the conference effort, this biaoerosol special issue was organized. This special issue consists of a total of 20 bioaerosol articles from eight countries including one review, and contributes to the advances in bioaerosol emission, transmission, health effects, ambient bioaerosols, method development and instrumentation, as well as control. Particularly, this special issue highlights the risks of hospital viral infection, animal-borne pathogen transmission, virus and endotoxin sampling, portable high volume sampler, breath-borne pathogens and dispersion, airborne pathogen detection and survival, ambient bioaerosol monitoring, and control technologies in different settings. Through this special issue, the bioaerosol community has obtained a better understanding of bioaerosol health risks facing mankind and correspondingly developed the strategies to confront the threats. In addition, this effort was also expected to help build a larger bioaerosol community in the scientific world. This special issue might serve as a starting point to not only link bioaerosol scientists from different continents, but also bring together people from various fields yet with an interest in bioaerosol to collectively advance the field further.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (NSFC) Distinguished Young Scholar Fund awarded to Maosheng Yao. It was also sponsored by his current ongoing NSFC grants (91543126, 21611130103, 21477003, 41421064) and the Ministry of Science and Technology (grants 2016YFC0207102, 2015CB553401, 2015DFG92040). Here, the guest editor appreciates all the efforts and supports provided by the reviewers during the review process. In addition, the guest editor is also thankful for all the attendees of the 600th Xiangshan Science Conference and also all the financial supports from the Xiansgshan Science Conference Office and also those from environmental companies in China.

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