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Review

Bioaerosol emissions from activated sludge basins: Characterization, release, and attenuation

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HIGHLIGHTS

• Activated sludge basins generate bioaerosols that transmit clinical pathogens.
• Bioaerosols are released via splashing and bubble bursting.
• Ecological characterization includes various culture and PCR analytical methods.
• Control strategies include covering, aeration adjustment, and free-floating media.

GRAPHICAL ABSTRACT

This article presents a critical review of the peer-reviewed literature related to bioaerosol generation from activated sludge basins. Characterization techniques include a variety of culture- and nonculture-based techniques, each with unique features. Bioaerosols contain a variety of clinical pathogens including Staphylococcus saprophyticus, Clostridium perfringens, and Salmonella enteritidis; exposure to these microorganisms increases human health risks. Release mechanisms involve splashing and bubble burst dynamics. Larger bubbles emit more aerosol particles than smaller ones. Attenuation strategies include covering sources with lids, adjusting the method and intensity of aeration, and using free-floating carrier media. Future studies should combine culture and non-culture based methods, and expand chemical databases and spectral libraries in order to realize the full power of real-time online monitoring.

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ABSTRACT

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1. Introduction

1.1. Bioaerosol characteristics and sources

Bioaerosols are airborne particles that include biological materials such as bacteria, fungi, pollen, viruses, their fragments and byproducts (e.g., endotoxins and mycotoxins), or animal allergens (Hinds, 1999; Pepper et al., 2015). Bioaerosols include liquid and may also feature physical interactions biological materials and inorganic matter (Pepper et al., 2015). In general, bioaerosols can be generated by a variety of outdoor activities (e.g., agriculture, waste management) and indoor sources (e.g., hospitals, laboratories), and they can be transported over large distances due to their size (i.e. 1 nm to 100 nm) and the effects of wind speed and molecular diffusion (Pepper et al., 2015).

1.2. Bioaerosol viability

The viability of airborne microorganisms is dependent on temperature, relative humidity, oxygen content, water content, UV radiation, and the presence of reactive chemicals (Hinds, 1999; Pepper et al., 2015). As a result, bioaerosol viability can vary considerably. Spore-forming bacteria, molds, and cyst-forming species have structural features that enhance survivability under stress (Pepper et al., 2015). Additionally, adherence to inert materials provides additional protection from oxidants (Berman et al., 1988; Templeton et al., 2005).

1.3. Bioaerosol impacts

Exposure to bioaerosols has been associated with various health effects including infectious diseases, acute toxic effects, allergies, and cancer. The most widely studied and probably most important bioaerosol-associated health effects are respiratory symptoms and impairment in lung function (Kim et al., 2018). While the majority of reviewed literature focuses on bioaerosol disease transmission, both natural and anthropogenic bioaerosols can also have beneficial impacts on the environment. Bioaerosol dissemination of pollen provides cross pollination of agricultural crops and forests (Calvo et al., 2018; Chamecki et al., 2011). Bacterial bioaerosols can be used as a non-chemical pesticide alternative (Betz et al., 2000; Edwards-Jones and Howells, 2001). Pollen and bacterial bioaerosols have also been shown to contribute to droplet nuclei formation to facilitate the formation of precipitation in clouds (Diehl and Wurzler, 2004).

1.4. Bioaerosols from wastewater treatment plants

Municipal wastewaters contain pathogenic viruses (including the new novel coronavirus SARS-CoV-2), multidrug-resistant bacteria, fungi, and other microorganisms (Metcalfe and Eddy, 2003; Lodder and de Roda Husman, 2020). These microorganisms can be launched into ambient air during wastewater treatment. Bioaerosol emissions have been reported at numerous wastewater treatment plants (Carducci et al., 2000; Ding et al., 2016; Gaviria-Figueroa et al., 2019; Heinonen-Tanski et al., 2009; Korzeniewska et al., 2009; Pascual et al., 2003; Tian et al., 2020) and outdoor concentrations near these facilities appear to be approximately an order magnitude higher than typical outdoor concentrations (Han et al., 2019; Hinds, 1999). Therefore, there are potential health hazards for operators and the general public.

1.5. Scope of review

This review focuses on bioaerosol emission from activated sludge basins. The topics will include characterization techniques, viability, release mechanisms, and attenuation. Bioaerosol emissions from pump stations, primary treatment, and sludge treatment are not included in this review. Finally, future research needs will be discussed, some of which will be based on gaps identified in the existing literature. This review may be used to guide work that can lead to improved methods for decreasing bioaerosol emission. To the best of our knowledge, this is the first review to cover these topics at length. An outline of this article is shown in Fig. A1 and the literature sources used in this review are summarized in Table A1.

2. Bioaerosol characterization

2.1. Bioaerosol collection

Sampling methods are based on the following methods originally developed for general airborne particles with or without modifications: (i) impingers, (ii) cyclones, (iii) impactors, (iv) filters, (v) spore traps, (vi) electrostatic precipitation, (vii) thermal precipitators, (viii)
condensation traps, and (ix) gravitational samplers (e.g. settle plates) (Kim et al., 2018). Impingers and cyclones collect the bioaerosols into a liquid medium, presumably a preferred choice than solid filters as they do not dry out and retain the microorganism viability. Impinger and cyclones can also use a broad array of liquid collection media that can be selected based on a specific microorganism of interest (Cooper et al., 2014). Impingers can also use non-evaporating liquid media including mineral oil to allow for long duration air samples of bacteria and fungi lasting up to several hours (Lin et al., 1999). The bioaerosol samples are eventually transferred onto plates or dissolved into a liquid solution for further microscopic examination, culturing experiments or non-cultured analysis such as PCR analysis. Efficiency of collection is dependent on the type of sampling method, materials of the sampler, operation parameters of the sampling devices and the microbial species (Kim et al., 2018).

2.2. Bioaerosol quantification methods

2.2.1. Culture-based techniques

Culture-based techniques are the most well-established and readily available for bioaerosol assessment. It is also a very sensitive technique and many different species can be identified without the need for specific biomarkers or primers. Culturable bioaerosols are normally sampled by using impactors (microorganisms are collected directly on a culture medium), liquid impinger (microorganisms are collected in liquid collection fluid) or air filtration methods (microorganisms are collected on a filter). The collected bioaerosols are then transferred to the lab and grown on petri dishes with a chosen media (e.g. LB, nutrient agar for bacteria; Sabouraud dextrose agar for fungi) for a few days (Yazdanbakhsh et al., 2020). Colonies can be counted manually or with the aid of image analysis techniques. Additionally, selective culture mediums are available to allow for the culture, identification, and quantification of a species of interest while inhibiting the growth of other microorganisms (Aithinne et al., 2019; Hustá et al., 2020). Culture-based techniques only measure the cultivable microorganisms and tend to underestimate the bioaerosol concentration due to several reasons that may cause viability loss. These factors include bioaerosol drying out in filtration-based sampling, atmospheric temperature, relative humidity, exposure to UV radiation (Douglas et al., 2017). Cellular aggregation can also cause large variations in culture-based data.

2.2.2. Non-culture-based techniques

Currently the most popular non-culture-based method is the polymerase chain reaction (PCR) method which detect and identify microorganisms and viruses by DNA or RNA sequence comparison. A genetic sequence representing a specific microorganism is first targeted by a carefully designed DNA primer, then amplified, quantified, and sequenced. The resulting sequences can then be analyzed directly and compared with existing public databases for identification and quantification. Bioaerosol samples are first eluted from the collection device and concentrated; DNA material is then extracted and purified for subsequent PCR analysis. The PCR method detects both cultivable and nonculturable microorganisms, thus circumventing the limitations imposed by culture-based techniques. Indeed, this method can be applied to any biological matter that contains nucleic acids and has been successfully applied to bioaerosols collected through a variety of sampling techniques (Peccia and Hernandez, 2006). Modern PCR-based methods also provide results more rapidly than culturing techniques (Peccia and Hernandez, 2006). The rapid developments in this technology have made it even more accurate, sensitive and also readily available to many laboratories. Because this method does not differentiate nucleic acid material from dead versus living microorganisms or cell debris, PCR results tend to overestimate the infectivity of bioaerosols.

Live unculturable microorganisms and dead but morphologically intact microorganisms can be also quantified by fluorescence-based methods. Non-culturable bioaerosols collected using air filtration or liquid impinger methods are transferred to the lab. There the microorganisms can be stained with a fluorophore (e.g. acridine orange or DAPI) that binds with nucleic acid, and counted with an epifluorescence microscope or flow cytometry. Using a combination of fluorescent dyes such as the live/dead BacLight assay, both live and dead microorganisms can be visualized and enumerated. Specific identification and quantification of a certain bacteria species is also possible with the use of fluorescently-labeled nucleic acid probes to target RNA within morphologically intact cells. The main advantage of these methods is that all microorganisms (i.e. cultivable and unculturable, dead and living) are quantified. The estimated bioaerosol concentration is therefore often higher than values determined using culture-based methods (Pepper et al., 2015).

Apart from whole microorganisms, bioaerosols also contain toxic or allergenic microbial byproducts that cannot be quantified by nucleic acid-based methods. The most common method for the detection of this type of bioaerosol is enzyme-linked immunoassays (ELISA). Toxin/allergen bioaerosol samples are first immobilized to a solid surface, a detection antibody which recognizes a specific antigen on the toxin/allergen is added. The detection antibody can be either directly linked to an enzyme or detected by a secondary antibody which is linked to an enzyme. When a substrate of the enzyme is added to the mixture, it produces a signal (e.g. chemiluminescence, fluorescence, absorbance) that correlates with the quantity of the antigen in the bioaerosol sample. ELISA assays have also been developed to detect and quantify microbial pathogens by detecting the antigens on the microbial surface. Successful applications include detection of bacterial endotoxins (Stratis-Cullum et al., 2003). E. coli (Korzeniewska and Harnisz, 2012), and mite allergen (Miyajima et al., 2014). The advantages of ELISA is its specificity and adaptability to direct field use; the disadvantage is that a good antibody is often required, which is not always available.

3. Bioaerosol release from activated sludge basins

3.1. The aeration basin

The aeration basin is a central feature in modern wastewater treatment process trains. The purpose of the aeration basin is to remove biodegradable wastewater constituents, primarily organic compounds and nitrogen. Large populations of prokaryotic and eukaryotic species are cultivated in the aeration basin by controlling pH, proper mixing, and providing oxygen as a terminal electron acceptor. Aeration is achieved with diffused aeration or mechanical mixing (e.g. surface aeration). The intense mixing and turbulence creates bioaerosol emission. Numerous studies have documented bioaerosol emission from aeration basins (Bauer et al., 2002; Brandt et al., 2000; Filipkowska et al., 2000; Han et al., 2019).

3.2. Microorganisms present in bioaerosols

Previous studies have used culture-dependent and culture-independent methods to identify the microorganisms present in bioaerosols emitted from aeration basins (Table 1). The primary focus of the culture-dependent work was the identification of known clinical pathogens including intestinal microorganisms (e.g. Enterococci sp., Enterobacter sp.) and bacteria that inhabit mucous membranes (e.g. Staphylococcus sp.). Therefore, exposure to bioaerosols emitted from aeration basins creates human health risks. Korzeniewska et al., 2009 also detected fungi, which are resilient in bioaerosols because of their ability to survive desiccation stress (Pepper et al., 2015). The culture-independent bioaerosol work of Gaviria-Figueroa et al., 2019 revealed the presence of a variety of microorganisms that have functional significance in the wastewater treatment process. For example, Candidatus Accumulibacter is responsible for phosphorus removal (Metcalf and Eddy, 2003). Nitrospira is responsible for the oxidation of nitrite, a
necessary step in the nitrification process (Metcalf and Eddy, 2003). Gaviria-Figueroa et al., 2019 also detected antibiotic resistance genes carrying organisms in bioaerosols.

Prolonged viability is a concern for bioaerosols released from aeration basins. Activated sludge microorganisms grow within flocculent aggregates, consisting of extracellular polymeric substances (EPS), inert particles, water, and numerous ionized chemicals (Metcalf and Eddy, 2003; Kurnacheva and Stuckney, 2014). The typical size range of these microstructures is 45 to 250 μm (Feng et al., 2019; Han et al., 2019; Yuan and Farnood, 2010), significantly larger than that of bioaerosol (size range ~1 nm to 100 nm, Pepper et al., 2015). However, some of the elements of the floc matrix can provide protection from the heat, UV radiation, and reactive oxygen species (ROS) present in the troposphere. Additionally, ROS may be reactively dissipated by functional groups found in EPS (i.e. N–H, O=H, C=O–C, C=O) (Jenkins et al., 2003; Wang et al., 2018) and by other byproducts excreted by bacteria (Ni et al., 2011). There is a need to further investigate the effect of activated sludge properties on bioaerosol viability and resilience.

3.3. Release mechanisms related to diffused aeration

Diffused aeration creates bubbles that rise to the top of the water column. When bubbles are on the surface, gravity draws the liquid down the sides of the bubble back to the bulk liquid, causing the membrane of the bubble to become thinner (Ke et al., 2017). The bubble then bursts when the membrane can no longer maintain the internal pressure of the bubble (Fig. 1A). As a bubble dissolves, the liquid remaining in the membrane splits into strands of liquid that then break into small droplets (Fig. 1B). If the bubble is only a few millimeters in diameter, a jet may form as water rushes to fill the void space created by the bubble on the surface (Fig. 1C). However, in larger bubbles, there is some confusion about the conditions that form jets; Ke et al. (2017) indicated that this jet does not form above a diameter of 3.4 mm, so that the only source of aerosols is from the droplets formed from the membrane during bursting. Lee et al. (2011) described jetting in the bursting of bubbles with a radius length much greater than 100 μm, but it is not quite clear whether these larger bubbles were as large as the ones examined in Ke et al. (2017). Bursting bubbles release pollutants and ions into the atmosphere (Hardy, 1982). Microorganisms accumulate in the interface that separates the bulk liquid from the atmosphere (Hermansson and Dahlbäck, 1983; Schäfer et al., 1998). Numerous studies have shown that bursting bubbles aerosolize the microorganisms present in the air-water interface (Aller et al., 2005; Baylor et al., 1977; Blanchard and Syzdek, 1970; Filipkowska et al., 2000). Larger bubbles emit more and larger aerosol particles than smaller ones (Ke et al., 2017).

3.4. Release mechanisms related to mechanical surface aeration

Surface aeration is commonly achieved with horizontal rotating brushes (Fig. 2). Droplets of various sizes are ejected from the water into the air off of the discs in all directions ((1) in Fig. 2). Many of these droplets may be too large to become aerosols and will simply fall back into the water. However, droplets <7 μm in diameter can be carried on moving air currents and are small enough to be deposited in the respiratory system during normal respiration (Donnison et al., 2004). Foams and bubbles are commonly observed near the rotating discs on the water surface ((2) in Fig. 2). Bioaerosols are released as these bubbles pop on the surface and by the splashing that occurs when droplets land on the water surface ((3) in Fig. 2, Fracchia et al., 2006; Li et al., 2013; Sánchez-Monedero et al., 2008). Bubbles form from the splashing of water caused by the rotation of the brushes ((4) in Fig. 2) and from the forcing of air down into the water column.

Splashing and bubble bursting occur with other methods of mechanical surface aeration (e.g. subsurface turbines, fountains, horizontal paddles), but peer-reviewed studies have not yet revealed the bioaerosol release mechanisms for these processes. Horizontal mixing rotors were found to produce higher aerosol emissions than surface turbines (Sánchez-Monedero et al., 2008). Surface aeration generates higher bioaerosol emissions than subsurface aeration (Bidaki et al., 2019).

4. Attenuation strategies

4.1. Covering sources

Aeration basins can be covered with light-weight materials which can be periodically cleaned or replaced. This approach is now commonly done for odor control (Metcalf and Eddy, 2003). Hinged lids have been used to cover bioaerosol sources at a full-scale treatment facility (Fernando and Fedorak, 2005). Other studies have recommended covering sources to reduce bioaerosol emissions (Fathi et al., 2017; Kummer and Thiel, 2008) or designing facilities so that sewage is not exposed to open air (O’Hara and Rubin, 2005).

The results in Fernando and Fedorak (2005) indicated that a floating cover apparently does not affect oxygen transfer for diffused aeration, but there may be a marginal reduction in oxygen transfer efficiency.
and energy efficiency (Ashley et al., 1992). Covers may also have small openings to allow for airflow out of the basin during aeration (Fernando and Fedorak, 2005), which may permit bioaerosol release. However, these hinged coverings may not be practical for certain mechanically-aerated systems. Since the mechanical aeration methods are designed to introduce open air into the wastewater, oxygen flow may be restricted when the basin is covered, resulting in a drop in the aeration efficiency of the rotors.

4.2. Aeration adjustments

Bioaerosol emissions from activated sludge basins are dependent upon the aeration method, which in turn influences mixing. Switching from surface aeration to fine bubble diffused aeration appears to reduce bioaerosol production (Bauer et al., 2002; Brandi et al., 2000; Fathi et al., 2017; Han et al., 2019; Sánchez-Monedero et al., 2008). Fernando and Fedorak, 2005 showed that changing from coarse bubble to fine bubble aeration decreased the bioaerosol concentrations from 1000 and 1800 CFU/m$^3$ to 24 and 37 CFU/m$^3$ and two locations near the aeration basins. Changing from coarse bubble aeration to fine bubble aeration is a promising strategy for attenuating bioaerosol release. This option also has the additional benefit of improving oxygen transfer efficiency (Metcalf and Eddy, 2003). However, the conversion may require a redesign of the apparatus delivering the air to the basins. Characteristics of the bioaerosols produced by these methods must also be considered. Although horizontal rotors exert stronger shear forces that produce more total bioaerosols, the size of those particles is predominantly greater than 7.0 $\mu$m (Han et al., 2020). Meanwhile, fine bubble aeration mainly produces smaller, respirable aerosols (Han et al., 2020).

4.3. Free-floating carrier media

Another strategy is the use of free-floating carrier media (FFCM), which consists of low-density materials that could be placed on the water surface to stop bioaerosol release. Bourke, and AON International, Inc. (1999) and Sheehy et al. (1984) described using plastic or polystyrene beads as FFCM to prevent mists from being released from electroplating tanks. Shredded foam has also been used because it may interlock better than sphere-shaped media (Bourke, and AON International, Inc., 1999).
Hung et al. (2010) used polystyrene spheres in a laboratory-scale bioreactor, and they found that the emission reduction increased as the sphere size (i.e., 1.9, 2.9, 3.4, 4.8 cm) decreased. They also showed that using multiple bead layers may provide a modest improvement in capture efficiency. For both the electroplating and sewage aeration experiments, free floating carrier media was effective at removing or preventing the release of most aerosol particles up to around 90% (Hung et al., 2010; Sheehy et al., 1984). Noh et al., 2019 found that the introduction of powdered activated carbon (PAC) in a membrane bioreactor increased the formation of bacterial flocs and decreased the amount of free bacteria available to be aerosolized. No FFMC studies have been carried out at a full-scale wastewater treatment plant to the best knowledge of the authors.

One of the challenges of using FFMC is that the aeration process may push the media along the water surface and away from the source of the bioaerosols, reducing their effectiveness as Hung et al. (2010) observed in their initial experiments. This could be especially problematic for mechanical aeration. FFMC may also need to be cleaned or replaced frequently. Different designs (e.g., shapes or sizes) of FFMC may be developed to correct for these effects in some cases, but the study of the limits and uses of FFMC for bioaerosol control is still in early stages.

5.1. Bioaerosol characterization methods

As aforementioned, currently there are various types of characterization methods available for bioaerosol measurement. Each type of method has advantages and disadvantages. Thus the first area of future research should focus on the side-by-side comparison and integration of different techniques. For example, bioaerosols of bacterial origin can be estimated with good accuracy with culture-based methods in combination with fluorescent labeling and microscopy. This is particularly important when the bioaerosols are not collected in liquid (e.g., filters) and may suffer viability loss due to drying out and loss during the recovery process. Bioaerosols of viral origin are often measured with a PCR-based method; however, the correlation between nucleic acid materials and actual infectivity is not always available for accurate risk assessment. Therefore, studies with side-by-side comparison of PCR and culture-based infection assays (e.g., integrated cell culture-PCR techniques, Reynolds et al., 2001; Reynolds, 2004) are needed to fill this knowledge gap. Paper-based devices that integrate virus extraction, purification, amplification, and detection have the potential for rapid, on-site field sensors (Mao et al., 2020). Similarly, ELISA-based portable sensors can be developed for on-site detection of bioaerosols containing toxins and other secreted substances.

Considerable progress has been made toward real-time online monitoring of bioaerosols (Tian et al., 2020), however, most of the techniques require further development and validation. Expanding the chemical database and spectral libraries and linking them to specific microbial origins should continue to be an area of active research. Integration of these techniques with sampling devices will require modification and improvement on the latter as well. In addition to high collection efficiency and minimal viability loss, the ideal bioaerosol sampler should also allow rapid and continuous sampling, easy integration with detection systems, portability, and automated operation (Cho et al., 2019).

5.2. Toward better attenuation strategies

Further study is needed to understand and develop improved attenuation strategies. There are relatively few peer-reviewed studies, limited data sets, and no predictive mathematical models (e.g., computational fluid dynamics models). Research is needed to validate previous findings and build consensus. Future studies should use a combination of modern characterization methods. Specifically, future research should:

1. Investigate covering bioaerosol sources with novel, reactive, self-cleaning materials, now available for numerous applications (Singh et al., 2020; Valenzuela et al., 2019).
2. Evaluate the role of FFMC surface properties (e.g., hydrophobicity) and adorption on bioaerosol attenuation; possible chemical interactions (e.g., van-der-Waals, hydrogen bonding) should be evaluated.

6. Conclusions

Activated sludge aeration basins generate bioaerosols that transmit a variety of clinical pathogens as well as strains responsible for sewage treatment processes. Bioaerosols are produced via splashing and bubble bursting, releasing microorganisms present in the air-water interface. Mechanical surface aeration generates higher bioaerosol emissions than diffused aeration, and coarse bubble diffused aeration generates more bioaerosol production than fine bubble diffused aeration. Prolonged viability is a concern because activated sludge contains numerous constituents - including EPS and inert materials - capable of providing protection to airborne microorganisms. Mitigation may be done by covering sources, adjusting the aeration method, and, possibly, by adding FFMC directly into the activated sludge basin. However, bioaerosol attenuation data is in short supply, there are few peer-reviewed studies, and there are no predictive mathematical models. Future research must pursue relevant lines of inquiry using a combination of modern characterization methods, and chemical databases and spectral libraries need to be expanded in order to fully realize the power of real-time online monitoring.

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CRediT authorship contribution statement

Adam Burdsall: Conceptualization, Methodology, Investigation, Writing - original draft preparation. Yun Xing: Writing - reviewing, and editing. Casey Cooper: Writing - reviewing. Willie F. Harper: Conceptualization, Investigation, Funding acquisition, Methodology, Supervision, Writing - original draft preparation, Writing - reviewing, and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Aithinne, K.A., Cooper, C.W., Lynch, R.A., Johnson, D.L., 2019. Toilet plume aerosol generation rate and environmental contamination following bowl water inoculation with Clostridium difficile spores. Am. J. Infect. Control 47 (5), 515–520. Aller, J.Y., Kuznetsova, M.R., Jahn, C.J., Kemp, P.F., 2005. The sea surface microlayer as a source of viral and bacterial enrichment in marine aerosols. Aerosol Science 36, 801–812. Ashley, K.J., Mavum, D.S., Hall, K.J., 1992. Bench-scale study of oxygen transfer in coarse bubble diffused aeration. Water Res. 26 (10), 1289–1295. Bauer, H., Fuhracker, M., Zibuschka, F., Schmidt, H., Puxbaum, H., 2002. Bacteria and fungi in aerosols generated by two different types of wastewater treatment plants. Water Res. 36, 3965–3970. Baylor, E., Peters, V., Baylor, M., 1977. Water-to-air transfer of virus. Science 197, 763–764. Berman, D., Rice, E., Hoff, J., 1988. Inactivation of particle-associated coliforms by chlorine and monochloramine. Appl. Environ. Microbiol. 54 (2), 507–512. Betz, F.S., Hammond, B.G., Fuchs, R.L., 2000. Safety and advantages of Bacillus thuringiensis-protected plants to control insect pests. Regul. Toxicol. Pharmacol. 32 (2), 156–173.
Cho, Y.S., Hong, S.C., Choi, J., Jung, J.H., 2019. Development of an automated wet-cyclone. J. Aerosol Sci. 109, 1–6.

Chamecki, M., Gleicher, S.C., Dufault, N.S., Isard, S.A., 2011. Diurnal variation in settling velocity of pollen released from maize and conseqences for atmospheric dispersion and cross-pollination. Agric. For. Meteorol. 151 (8), 1055–1065.

Cho, Y.S., Hong, S.C., Choi, J., Jung, J.H., 2019. Development of an automated wet-cyclone system for rapid, continuous and enriched bioaerosol sampling and its application to real-time detection. Sensors & Actuators: B Chemical 284, 525–533.

Cowan, A.J., Ball, G.J., 2014. Comparison of high-volume air sampling equipment for viral aerosol sampling during emergency response. Journal of Emergency Management 12 (2), 161–170.

Diehl, D.S., Pilger, C.S., 2009. Generation of the model calculations considering soluble and insoluble particles in the drops. J. Atmos. Sci. 61 (16), 2063–2072.

Ding, W., Li, H., Han, Y., Liu, J., Liu, J., 2016. Site-related and seasonal variation of bioaerosol emission in indoor wastewater treatment station: level, characteristics of particle size, and microbial structure. Aerobiologia 32, 211–224.

Donnison, A., Ross, C., Noonan, M., Fisher, G., Waller, J., 2004. Bacterial survival and dispersion of microbial aerosols. N. Z. J. Agric. Res. 47, 575–585.

Douglas, P., Hayes, E.T., Williams, W.B., Tyrell, S.F., Kinnersley, R.P., Walsh, K.O., D’Orioddick, M., Longhurst, P.J., Pollard, S.J., Drew, G.H., 2017. Use of dispersion modelling for environmental impact assessment of biological air pollution from composting: progress, problems and prospects. Waste Manag. 70, 22–29.

Edwards-Jones, G., Howells, O., 2001. The origin and hazard of inputs to crop protection in organic farming systems: are they sustainable? Agric. Syst. 67 (1), 31–47.

Edwards, J.T., 1982. The sea surface microlayer: biology, chemistry and anthropogenic enrichment. Progress in Oceanography 11, 307–328.

Ehrenberg, T., 1997. The sea surface microlayer: biology, chemistry and anthropogenic enrichment. Research on Coastal 9, 317–328.

Fathi, S., Hajjiazadeh, Y., Nikaem, M., Gorbani, M., 2017. Assessment of microbial aerosol emission from an indoor wastewater treatment plant operated with activated sludge process. Aerobiologia 33, 507–515.

Feng, Q., Tai, X., Sun, Y., Li, M., 2019. Influence of turbulent mixing on the composition of extracellular polymeric substances (EPS) and aggregate size of aerated activated sludge. Chem. Eng. J. 378, 122123.

Fernando, NL, Fedorak, PM., 2005. Changes at an activated sludge sewage treatment plant alter the numbers of airborne aerobic microorganisms. Water Res. 39, 4597–4608.

Filipkowska, Z., Janczukowicz, W., Krzemieniewski, M., Pesta, J., 2000. Microbiological air pollution in the surroundings of the wastewater treatment plant with activated sludge. J. Aerosol Sci. 31, 2566–2573.

Gavría-Figueroa, A., Preiner, E.C., Hogue, S., Feigley, C.E., Norman, R.S., 2019. Emission and dispersal of antibiotic resistance genes through bioaerosols generated during the treatment of municipal sewage. Science of the Total Environment 688, 402–412.

Han, Y., Xiao, X., Li, X., Cai, R., Cantiello, L., Fezzaa, K., Lee, W.K., 2017. Characterization of aerosol emissions from aquaculture waste water treatment processes. J. Hazard. Mater. 329, 374–375.

Han, Y., Yang, T., Zhang, Y., Wang, C., 2019. Relationship between ambient aerosols and aerosols in typical indoor environments in Taipei. J. Aerosol Sci. 30, 6571–6572.

Lodder, W., de Roda Husman, A.M., 2020. SARS-CoV-2 in wastewater: potential health risk, but also data source. The Lancet Gastroenterology & Hepatology 5 (6), 533–534.

Metcalf and Eddy, 2003. Wastewater Engineering Treatment and Reuse. Fourth edition. McGraw Hill Inc., New York, NY.

Miayjima, K., Suzuki, Y., Miki, D., Araki, M., Arakawa, T., Shimoura, H., Shiba, K., Mitsuhashi, K., 2014. Direct analysis of airborne mite allergen (Der f1) in the residential atmosphere by chemiluminescent immunosay using bioaerosol sampler. Talanta 123, 241–256.

Noh, J.H., Choi, H., Kim, H.Y., Choi, S., Maeng, S.K., 2019. Reducing bacterial aerosol emissions from membrane biofuel: the effects of SRT and the addition of PAC and calcium chloride. Water Res. 156, 246–256.

O’Hara, R.E., Robin, R., 2005. Reducing bioaerosol dispersion from wastewater treatment and its land application: a review and analysis. J. Environmental Health 68 (2), 24–29.

Pascual, L., Pérez-Lu, Y., Matazá, M.A., Santamaria, A., Gibert, K., Salgör, M., Apraza, D., Catalán, V., 2003. Bioaerosol emission from wastewater treatment plants. Aerobiologia 19 (3–4), 261–270.

Peccia, J., Hernandez, M.2006. Incorporating polymerase chain reaction-based identification, population characterization, and quantification of microorganisms into aerosol science: a review. Atmosphere 7, 31–47.

Pepper, I.L., Gerba, C.P., 2015. Environmental Microbiology. Academic Press Publishers, Waltham, MA-02495-076.

Peccia, J., Hernandez, M., 2006. Incorporating polymerase chain reaction-based identification, population characterization, and quantification of microorganisms into aerosol science: a review. Atmosphere 7, 31–47.

Reda, M., Abu Al-Ela, M., Monnier, L., 2019. A comparison of sampling methods for the collection of bioaerosol. J. Aerosol Sci. 515, 1–14.

Reynolds, K., 2004. Integrated cell culture/PCR for detection of enteric viruses in environmental samples. Method. Mol. Biol. 268, 69–76.

Reynolds, K.A., Gerba, C.P., Abbaszadegan, M., Pepper, L.L., 2001. ICC/PCR detection of enteroviruses and hepatitis A virus in environmental samples. Can. J. Microbiol. 47 (2), 153–157.

Sánchez-Monedero, M.A., Aguilar, M.F., Renson, R., Roig, A., 2008. Effect of the aeration system on the levels of airborne coaggregates generated at wastewater treatment plants. Water Res. 42, 3739–3744.

Schäfer, A., Harms, H., Zehnder, A., 1998. Bacterial accumulation at the air-water interface. Environ. Sci. Technol. 32 (23), 3704–3710.

Shelby, J., Mortimer, J., Jones, S., Woodacre, S., 1984. Control Technology Assessment: Metal Plating and Cleaning Operations. NIOSH Technical Report. U. S. Department of Health and Human Services (119p).

Singh, V., Mishra, D., Kabachkov, E., Shul'ga, Y., Vaish, R., 2020. The characteristics of BICO/PLAst of Paris composites and their photocatalytic performance under visible light illumination for self-cleaning. Materials Science for Energy Technologies 3, 29–307.

Stilbs-Cullum, D.N., Griffin, D.G., Mobjely, J., Vass, A.A., Vo-Dinh, T., 2003. A miniature biochip system for detection of aerosolized Bacillus globigii spores. Anal. Chem. 75 (2), 275–280.

Templeton, M., Andrews, R., Hofmann, R., 2005. Inactivation of particle-associated viral surrogates by ultraviolet light. Water Res. 39 (15), 3487–3500.

Tian, J.-H., Yan, C., Nasir, Z.A., Garcia-Acega, S., Tyrrel, S., Coulon, F., 2020. Real time detection and characterization of bioaerosol emissions from wastewater treatment plants. Sci. Total Environ. 712, 137269.

Valenzuela, L., Iglesias, A., Faraldos, M., Bahamonde, A., Rosal, R., 2019. Antimicrobial surfaces with self-cleaning properties functionalized by photocatalytic ZnO electrospayed coatings. J. Hazard. Mater. 365, 609–615.

Wang, B.-L., Liu, X.-T., Chen, J.-M., Peng, D.-C., He, F., 2018. Composition and functional group characterization of extracellular polymeric substances (EPS) in activated sludge: the impacts of polymerization degree of proteinaceous substrates. Water Res. 129, 133–142.

Wei, M., Yu, Z., Zhang, H., 2015. Molecular characterization of microbial communities in activated sludge: the implications of polymerization degree of proteinaceous substrates. Water Res. 129, 133–142.

Yuan, Y., Farnood, R., 2010. Strength and breakage of activated sludge flocs. Powder Technol. 199 (5), 111–115.