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A short review of bioaerosol emissions from gas bioreactors: Health threats, influencing factors and control technologies

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HIGHLIGHTS
- The biofiltration generally emit more than 10^4 CFU m^-3 bioaerosol.
- The bioaerosol emitted from the biofiltration is a potential threat to human body.
- Shear force and dilution affect the concentration of bioaerosol emissions.
- PCD is promising to control bioaerosols because of few secondary pollutants.

ABSTRACT
Bioaerosols have widely been a concern due to their potential harm to human health caused by the carrying and spreading of harmful microorganisms. Biofiltration has been generally used as a green and effective technology for processing VOCs. However, bioaerosols can be emitted into the atmosphere as secondary pollutants from the biofiltration process. This review presents an overview of bioaerosol emissions from gas bioreactors. The mechanism of bioaerosols production and the effect of biofiltration on bioaerosol emissions were analyzed. The results showed that the bioaerosol emission concentrations were generally exceeded 10^4 CFU m^-3, which would damage to human health. Biomass, inlet gas velocity, moisture content, temperature, and some other factors have significant influences on bioaerosol emissions. Moreover, as a result of the analysis done herein, different inactivation technologies and microbial immobilization of bioaerosols were proposed and evaluated as a potential solution for reducing bioaerosol emissions. The purpose of this paper is to make more people realize the importance of controlling the emissions of bioaerosols in the biofiltration process and to make the treatment of VOCs by biotechnology more environmentally friendly. Additionally, the present work intends to increase people’s awareness in regards to the control of bioaerosols, including microbial fragment present in bioaerosols.

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1. Introduction

Biotechnology has become an important technology to control air pollution in the past decades (Kummer and Thiel, 2008; Deshusses, 1997). For instance, bioreactor provides a clean, cost-effective and environmentally friendly technology (Alonso et al., 1998; Esquivel-Gonzalez et al., 2017). Biofiltration processes are based on the ability of microorganisms to attach to packing media in the form of biofilms (Groenestijn and Kraakman, 2005; Kim et al., 2007; Yang et al., 2011). During the processing exhaust gas, these pollutants are absorbed by the biofilm and converted into carbon dioxide (CO₂), water (H₂O), and biomass without generating undesirable by-products (Devinn et al., 1999; Kennes, 2012). Biotechnology can effectively control low-concentration pollutants...
Therefore it has been successfully applied to treat a wide range of pollutants such as VOCs and odors (Mudliar et al., 2010; Girard et al., 2011).

Biotechnology has many advantages for VOCs treatment (Martens et al., 2001; Sanchez-Monedero et al., 2003; Schlegelmilch et al., 2005; Chmielowiec-Korzeniowska et al., 2007). However, it still has some drawbacks, such as the emission of bioaerosols (Wang et al., 2009; Yang et al., 2018). Bioaerosols are very small particles suspended in the air that are living or coming from living organisms (Burge, 1990; Després et al., 2012). Activated sludge and compost, often used as inoculation sources for biofilters, contain a large number of pathogenic bacteria, fungi, and viruses, etc. This might cause the release of bioaerosols containing pathogenic microbial microorganisms and microbial fragments during the biofiltration process, posing a great potential threat to human health (Ottengraf and Konings, 1991; Robertson et al., 2019; Menetrez et al., 2009; Ghosh et al., 2015; Zhou et al., 2016). Some studies have shown that bioaerosol emission concentrations from bioreactors are usually higher than those of the background environment (Kummer and Thiel, 2008; Chung, 2007; Esquivel-Gonzalez et al., 2017). Long-term exposure to bioaerosols in these environments may have adverse health effects (Pearson et al., 2015).

Studies on the emissions of bioaerosols produced from biofilters have been increasing recently. However, the available studies have not comprehensively summarized and presented the state of bioaerosol emissions from biofilters. This paper reviewed the formation and emission of bioaerosols from biofilters, the potential impacts, the influencing factors on bioaerosol emissions and relevant control technologies, which was expected to contribute to better understand the impacts and to raise awareness on the need to curb the bioaerosol emissions, with the ultimate goal of helping to achieve complete control of these substances.

2. Formation and emission of bioaerosols during biofiltration

2.1. Principle of the formation and emission of bioaerosols

Biofiltration for VOCs removal is a complex combination of different physicochemical and biological phenomena. VOCs and oxygen pass through the packing media. Pollutants are transferred from the gas phase to the water phase and biofilm phase by diffusion before biodegradation (Cheng et al., 2016). Microorganisms in the biofilm use VOCs as carbon sources to produce CO2, H2O, and biomass, etc. Microorganisms attach to the packing materials either naturally or as a result of engineering measures (Cohen, 2001).

Fig. 1 illustrates the basic principle of the formation and emission of bioaerosols from biofilters. During biofiltration, the airflow containing VOCs provides carbon sources for the biofilm. Over long periods of operation, a large amount of biomass accumulates and the biofilm attached to the surface of the packing materials becomes thicker simultaneously (Yang et al., 2010). Thicker biofilms make it easier for microorganisms to exchange with air currents and be carried away from the packing materials. Moreover, not only dead microorganisms, but also injured microorganisms, fragments of cells, mycotoxins and endotoxins proteins liberated during the lysis process of cells will also fall off the packing materials during the growth of microorganisms in the biofilm. Finally, bioaerosols will be released from the biofilters in the exhaust gas, carrying considerable amounts of microbes out of the biofiltration process.

2.2. Characteristics of bioaerosol emissions from biofilters

Some studies have reported that the outlet’s bioaerosol concentration of biofilters is in the order of 10³–10⁴ CFU m⁻³ air.

![Fig. 1. Phenomena involved in the formation and emission of bioaerosol in biofiltration.](image-url)
cultured cells. In fact, these cells make up at most about 20% of the bioaerosol concentration. Nonetheless, using this technique counting method (Saucedo-Lucero et al., 2014). Actually, dead microbes including the endotoxins and mycotoxins they produce can also cause damage to the human body (Görny, 2020). Also, Table 1 shows that the bioaerosols emitted from biofilters contain different microbial species. Depending on the source of the inoculum, the species of microbes present in the biofilters are different. Bacteria and fungi were often detected from biofilters inoculated from activated sludge and compost in previous studies (Sanchez-Monedero et al., 2003; Chung, 2007; Wang et al., 2018; Valdez-Castillo et al., 2019). Molds and spores were also presented in bioaerosols, which would cause inflammation and discharge (Ottengraf and Konings, 1991; Schlegelmilch et al., 2005; Vergara-Fernández et al., 2012a; 2012b).

2.3. Potential harm caused by bioaerosols

Bioaerosols may cause respiratory problems, eye irritation, rash, and diarrhea due to the inclusion of microorganisms (viable or inanimate) and/or microbial metabolites (Husman, 1996; Menetrez et al., 2009). Some studies have shown that bioaerosols contain some pathogenic microorganisms (Liu et al., 2018; Balloy and Chignard, 2009; Cerdeno-Tarraga et al., 2003). Table 2 presents some of the pathogenic species in the bioaerosols reported in the literature, indicating the diversity of pathogenic species. Although bioaerosols come into contact with the human skin, most illnesses are caused by the body inhaling pathogenic microorganisms into the respiratory tract. Legionella pneumophila (L. pneumophila) and adenovirus are typically pathogenic organisms, causing respiratory disease, which have been detected in the air of wastewater treatment plants (WWTPs) (Dong et al., 2018; Masclaux et al., 2014).

Some studies have presented that there are some qualitative evidence linking bioaerosol emissions from composting facilities to poor respiratory health in nearby residents (Pearson et al., 2015). This is mainly due to the exposure of many pathogenic microorganisms to the air during the waste treatment process. The risk of waste treatment workers may depend on their specific occupational tasks, the proximity to the source of bioaerosols and the emission reduction systems used on-site (Douwes et al., 2003; Pearson et al., 2015). L. pneumophila has been found not only from WWTPs and compost facilities, but also in the lungs of operators at these conditions, which has high-profile pathogenic bioaerosol-transmitted infection ability (Casati et al., 2010; Subbaram et al., 2017; Dong et al., 2018).

Table 3 shows some of the pathogenic microorganisms that are present during the waste treatment process (Cai and Zhang, 2013; Wéry et al., 2008). Not only pathogenic microorganisms, but also pathogenic viruses are present in the waste treatment processes (Otawa et al., 2007; Wu and Liu, 2009). Several studies have shown that these pathogenic entities become bioaerosols that are emitted into the air during waste treatment (Bauer et al., 2002). Some opportunistic pathogenic species including Acinetobacter sp., Pseudomonas sp., Enterococcus sp., and Bacillus sp. were isolated from the air emissions of wastewater treatment plants (WWTPs), which would cause respiratory disease, urinary tract infection, skin infection and septicemia, etc (Fracchia et al., 2006; Uhrbrand et al., 2017). Ibanga et al. (2018) also presented that A. Fumigatus was emitted from a biofilter ranged of 1 × 103 to 4.2 × 103 CFU m−3. It has been reported that more than 90% of pulmonary fungal diseases were caused by A. Fumigatus (Lagé, 2001). Moreover, some epidemic viruses have been detected in feces (Ding et al., 2004), including the 2019-nCoV reported by the Chinese Center for Disease Control and Prevention’s news. Since the activated sludge (including feces) and compost are often used as inoculation microorganisms in biofilters (from Table 1), the biofilters as a potential source of the human epidemic virus can not be ignored.

3. Factors influencing bioaerosol emissions

Operating conditions including biomass, inlet gas velocity, moisture content, temperature, can affect the bioaerosol emissions from biofilters (Zilli et al., 2005; Vergara-Fernández et al., 2012a; Esquivel-Gonzalez et al., 2017).

3.1. Influence of the biomass

Some results have shown that biomass will affect bioaerosol emissions and higher biomass accumulation in biofilter leads to higher bioaerosol emission concentrations. Zilli et al. (2005) reported that the bioaerosol emission concentrations from the biofilter filled with sieved sugarcane bagasse were higher than those of the biofilter filled with peat under the same gas velocities, and the bioaerosol emission concentrations increased linearly as biomass increased. With the increase of the biofilm thickness, the binding force between the biofilm and the packing materials became weak, which caused the microorganisms to be carried by the airflow and emitted from the biofilter in the form of bioaerosols (Chung, 2007; Vergara-Fernández et al., 2012a; Zilli et al., 2005; Wang et al., 2018).

Wang et al. (2009) also presented that the bioaerosol emission concentrations decreased in a combined process of UV-biofilter. The bioaerosol emission concentrations were reduced from 1.38 × 103 CFU m−3 to less than 70 CFU m−3 when UV was used in the pretreatment stage. This is owing to the ozone generated by UV light that killed the microorganisms, then reduced the biomass in the biofilter.

3.2. Influence of the gas velocity

Gas velocity determines the shearing force between the biofilm and airflow, which affects the bioaerosol emissions. Fig. 2 shows that when the gas velocity rises from 40 to 140 m h−1, the total bioaerosol concentrations rise from 200 to 800 CFU m−3 (Wang 2009).
### Table 1
Compilation of the literature encompassing bioaerosol emissions from biofiltration.

| Types of reactor | Packing materials | Inoculum source | Types of bioaerosol filtration | Outlet Concentration | References |
|------------------|-------------------|-----------------|--------------------------------|----------------------|------------|
| Full-scale Biofilters | Compost; peat and heather branches; compost and polystyrene particles | Compost | Bacteria and molds | (1) Different Specifications | Ottengraf and Konings, 1991 |
|                  |                   |                 |                                | Bacteria: 1020–9350 CFU m\(^{-3}\) |           |
|                  |                   |                 |                                |  Molds: 19–1180 CFU m\(^{-3}\) |           |
|                  |                   |                 |                                | (2) Different Gas velocity |           |
|                  |                   |                 |                                | Bacteria: 400–6630 CFU m\(^{-3}\), 79–634 m h\(^{-1}\) |           |
|                  |                   |                 |                                | Molds: 3–710 CFU m\(^{-3}\), 79–634 m h\(^{-1}\) |           |
| Biofilter | Coconut fibre/peat, chopped wood/bark and pellets/bark | Compost | Bacteria and fungi | 7.4 \(\times\) 10\(^{2}\)–4.9 \(\times\) 10\(^{3}\) CFU m\(^{-3}\) | Martens et al. (2001) |
| Biofiltration | | Compost | A. Fumigatus and Mesophilic Bacteria | Average: 1.1 \(\times\) 10\(^{3}\) CFU m\(^{-3}\) | Sanchez-Monedero et al. (2003) |
| Bioscrubber/ biofilter combination | Coke/wood or coconut fibre | Compost | Bacteria (Mesophilic/ thermophilic); Molds (Mesophilic/ thermophilic); Actinomycetes (thermophilic) | 3.7 \(\times\) 10\(^{3}\)–4 \(\times\) 10\(^{3}\) CFU m\(^{-3}\) | Schlegelmilch et al. (2005) |
| Biofilter | Peat or sieved sugarcane bagasse | Compost | Bacteria and fungi | 1 \(\times\) 10\(^{3}\)–4 \(\times\) 10\(^{3}\) CFU m\(^{-3}\) | Zilli et al. (2005) |
| Biofilter | Activated carbon and sludge | Compost | Bacteria and fungi | Without reduction device: 4 \(\times\) 10\(^{2}\)–1 \(\times\) 10\(^{3}\) CFU m\(^{-3}\) | Chung (2007) |
| Novel biofilter | Compost and peat; bentonite, compost and peat; halloysite, compost and peat | Compost | Mesophilic bacteria; Thermophilic actinomycetes | Total mesophilic bacteria: 0.3525 \(\times\) 10\(^{3}\) CFU m\(^{-3}\) | Chmielowiec-Korzeniowska et al. (2007) |
| Ultraviolet-Biofilter | Bamboo | Polluted soil | Fusarium solani (spores) | Temperature: 1 \(\times\) 10\(^{3}\) CFU m\(^{-3}\) | Wang et al. (2009) |
| Biofilter (step-feed) | Vermiculite | Pure bacteria | Fusarium solani (spores) | 1.8 \(\pm\) 0.5 \(\times\) 10\(^{3}\) CFU m\(^{-3}\) \(\mu\)C (average) | Vergara-Fernández et al., 2012a |
| Biofiltration | Vermiculite | Pure bacteria | Fusarium solani (spores) | Temperature: 8 \(\times\) 10\(^{3}\) CFU m\(^{-3}\) \(\mu\)C, 15 °C | Vergara-Fernández et al., 2012b |
| Biofilter | Perlite or Tezontle | Activated sludge | Fungi; Gram-negative bacteria; Gram-positive bacteria | 6.4 \(\times\) 10\(^{3}\)–1.3 \(\times\) 10\(^{4}\) cells m\(^{-3}\) \(\mu\)C (average) | Esquivel-Gonzalez et al. (2017) |
| Biofilter | Sawmilled wooden chips | Sewage sludge | — | — | Soret et al. (2018) |
| Biofilter | Perlite and ceramic | Activated sludge | Bacteria and fungi | (1) Gas velocity \(40–160 \text{ m h}^{-1}\) | Wang et al., 2018 |
| FTR (full-scale thermophilic biofilter) | Polyurethane foam cubes | — | Pseudomonas sp. (bacteria) | Nearly 2.3 \(\times\) 10\(^{3}\) CFU m\(^{-3}\) | Yang et al. (2018) |
| Biofilter | Polyurethane foam cubes | — | Sulfur-oxidizing bacteria (SOB); \(\alpha\)-xylene-degrading bacteria (XB); Acinetobacter lwofii and Aeromonas sp. | Total: 262 \(\pm\) 16–392 \(\pm\) 38 CFU m\(^{-3}\) (48 CFU m\(^{-3}\) of SOB and 93 CFU m\(^{-3}\) of XB) | Sun et al. (2018). |
| Pilot-scale biofilter | Wood chips | — | Bacteria and fungi | Total fungi: 1.3 \(\times\) 10\(^{3}\)–8 \(\times\) 10\(^{3}\) CFU m\(^{-3}\) | Ibang et al. (2018) |
| Biofilter-photoreactor | Perlite | Activated sludge | Bacteria and fungi | Aspergillus Fumigatus: 1 \(\times\) 10\(^{3}\)–4.2 \(\times\) 10\(^{3}\) CFU m\(^{-3}\) | Valdez-Castillo et al. (2019) |
| | | | | Total fungi: 1.3 \(\times\) 10\(^{3}\)–8 \(\times\) 10\(^{3}\) CFU m\(^{-3}\) |                 |
| | | | | Total mesophilic bacteria: 1.9 \(\times\) 10\(^{3}\) |                 |
| | | | | Gram negative bacteria: 1.3 \(\times\) 10\(^{3}\)–6.1 \(\times\) 10\(^{3}\) CFU m\(^{-3}\) |                 |
| | | | | Bacteria: average 48.90 \(\pm\) 27.0 \(\times\) 10\(^{6}\) Cell\(_{\text{bacteria}}\) m\(^{-3}\) \(\mu\)C with ZnO/Perlite system |                 |
| | | | | average 21.55 \(\pm\) 8.5 \(\times\) 10\(^{6}\) Cell\(_{\text{bacteria}}\) m\(^{-3}\) \(\mu\)C with TiO\(_{2}\)/Perlite system |                 |
| | | | | Fungi: average 3.74 \(\pm\) 2.1 \(\times\) 10\(^{6}\) Cell\(_{\text{fungi}}\) m\(^{-3}\) \(\mu\)C with ZnO/Perlite system |                 |
| | | | | average 2.68 \(\pm\) 0.8 \(\times\) 10\(^{6}\) Cell\(_{\text{fungi}}\) m\(^{-3}\) \(\mu\)C with TiO\(_{2}\)/Perlite system |                 |
et al., 2018). Nevertheless, the bioaerosol concentration drops again when the gas velocity exceeds 160 m h\(^{-1}\). An estimation of the shearing force exerted by the gas on the biofilm in a biofilter bed can be obtained using the Blake-Kozeny equation (Bird et al., 1960):

\[
q = \frac{4f}{\pi d^2} \rho u^2
\]

where \(f\) is the friction factor; \(a\) is the specific surface area; \(d_p\) is the particle size; \(\rho\) is the gas density; \(u\) is the gas superficial velocity.

This phenomenon may be related to the microbial flux on the surface of the packing materials and the dilution effect of gas emissions. It confirms that high gas velocity results in a strong shearing force on the biofilm, which makes it easy for microorganisms to be carried away from the packing materials (Lin et al., 2016; Wang et al., 2018). Nicolella et al. (1996) also demonstrated that the detachment rate was strongly increased with superficial velocity. High gas velocity is not suitable for microbe aggregation, causing microbe slough off from carriers to the air flow. The thickness of the biofilm also became thin under these conditions (Vergara-Fernández et al., 2012a). When the gas velocity reaches a certain flow rate, the biofilm would not fall off with the increase of gas velocity. Then the bioaerosol emission concentrations would decrease due to the dilution effect.

### 3.3. Influence of the temperature

The gas temperature will also affect the bioaerosol emission concentration (Vergara-Fernández et al., 2012b; Wang et al., 2018). High temperatures cause a decrease in the bioaerosol emission concentrations. Fig. 3 shows the effect of temperature on bioaerosol emissions (Wang et al., 2018). The total concentration of bioaerosol emissions achieves the highest value at 30 °C, while their concentration gradually decreases with further increasing temperature. High temperatures can cause cell lysis, and the biofilm and biomass accumulation rate will be negative, resulting in lower concentrations of bioaerosol (Vergara-Fernández et al., 2012b). Moreover, high temperatures can accelerate the heat exchange rate between the airflow and the biofilm, which would lead to the loss

### Table 2

| Pathogenic microorganisms | Kingdom | Harm       | Reference          |
|---------------------------|---------|------------|--------------------|
| L. pneumophila            | Bacteria| Pneumonia  | Dong et al. (2018) |
| M. tuberculosis           | Bacteria| Tuberculosis| Bonfait et al. (2017) |
| S. aureus                 | Bacteria| Abscesses  | Breza-Boruta (2016) |
| P. Fluorescens            | Bacteria| Inflammation| Breza-Boruta (2016) |
| Penicillium sp.           | Fungi   | Lung damage| Breza-Boruta (2016) |
| Aspergillus sp.           | Fungi   | Lung damage| Ibanga et al. (2018) |
| Cladosporium sp.          | Fungi   | Lung damage| Breza-Boruta (2016) |
| Adenovirus                | Virus   | Pneumonia  | Mascaux et al., 2014 |
| \(\beta\)-lactam ARGs     | ARGs    | Drug resistance| Wang et al. (2019c) |
| Tetracycline ARGs         | ARGs    | Drug resistance| Wang et al. (2019c) |
| Sulfonamide ARGs          | ARGs    | Drug resistance| Wang et al. (2019c) |
| Quinolone ARGs            | ARGs    | Drug resistance| Wang et al. (2019c) |
| Macrolide ARGs            | ARGs    | Drug resistance| Wang et al. (2019c) |

ARGs is an abbreviation for antibiotics resistance genes.

### Table 3

| Pathogenic microorganisms | Species | Health impact | Persistence in waste treatment | Infectivity |
|---------------------------|---------|---------------|---------------------------------|-------------|
| C. perfringens            | G-      | ●             | ●                              | ●           |
| E. faecalis               | G+      | ●             | ●                              | ●           |
| E. coli                   | G-      | ●             | ●                              | ●           |
| L. pneumophila            | G-      | ●             | ●                              | ●           |
| N. meningitidis           | G-      | ●             | ●                              | ●           |
| S. boydi                  | G-      | ●             | ●                              | ●           |
| S. dysenteriae            | G-      | ●             | ●                              | ●           |
| S. flexneri               | G-      | ●             | ●                              | ●           |
| V. cholerae               | G-      | ●             | ●                              | ●           |
| Salmonella spp.           | G-      | ●             | ●                              | ●           |
| C. jeani                  | G-      | ●             | ●                              | ●           |
| Enterococcus spp.         | G+      | ●             | ●                              | ●           |

(Species: Gram-positive bacteria: G+; Gram-negative bacteria; Level: High: ●; Moderate: ○; Low: ○).
of water in the microorganisms and affect their survival rates. High temperatures also caused microbial protein denaturation, which could affect microbial metabolism.

Furthermore, the gas temperature will affect the species of bioaerosol emissions. Wang et al. (2018) found that fungal bioaerosol concentrations were higher than bacterial’s when the temperature was below 40 °C, while bacterial bioaerosol concentrations were higher than fungal’s when the temperature was above 50 °C. This was due to differences in the growth and metabolic capacity of different microorganisms at different temperatures. Also, when gas temperature increased, these unfavorable factors would promote fungi to form spores, thereby increasing the concentration of spore bioaerosols. Vergara-Fernández et al. (2012b) presented that higher concentrations of spore bioaerosol occurred when the temperature was 35 °C, while lower concentrations of spore bioaerosol occurred when the temperature was 25 °C.

3.4. Influence of the moisture content

The moisture content of packing materials will affect the emission of bioaerosol, and high moisture content will reduce bioaerosol emissions. Fig. 4 presents that the total bioaerosol concentrations decrease when the moisture content exceeds 70% (Wang et al., 2018). The water film thickness would maintain with the increase of moisture content, which would reduce the exposure of the biofilm to the airflow and the carrying of microorganisms by the airflow.

The moisture content will also affect the content of bioaerosol. Wang et al. (2018) presented that the peak concentration of bacteria was achieved with a moisture content of 70%, while fungi were achieved with a moisture content of 40%. This phenomenon might be explained by the fact that fungi are more suitable for growing in a dry environment, while bacteria are more suitable for growth in humid environments. Meanwhile, the higher moisture content will also reduce the content of spores in bioaerosols. The decrease in irrigation frequency brought about a gradual reduction in the moisture content of the bed, which promoted the emission of spores increased (Saucedo-Lucero et al., 2014). Vergara-Fernández et al. (2012b) also found that spore emission concentrations were decreased from about $2.2 \times 10^3$ CFU m$^{-3}$ air to about $1.3 \times 10^3$ CFU m$^{-3}$ air when the moisture content increased from 20% to 80%.

3.5. Influence of other factors

Other design and operating factors, such as packing materials, inoculation sources, and nutrients also influence bioaerosols emissions (Alvarez-Hornos et al., 2008; Vergara-Fernández et al., 2012a, 2012b; Esquivel-Gonzalez et al., 2017).

According to the schematic diagram shown in Fig. 1, microorganisms need to be attached to the packing materials during the operation of the biofilter. For different packaging materials, the porosity, particle size, and specific surface area are different, which leads to different environments for the growth of microorganisms and influences the accumulation rate of microorganisms. Larger particle sizes would result in higher biomass concentrations (Nicollella et al., 1996). Esquivel-Gonzalez et al. (2017) found that perlite was better than Tezontle with a lower bioaerosol emission, which was due to a smaller diameter of perlite in their study. Ottengraf and Konings (1991) also presented that the concentration and composition of bioaerosols are different during the operation of the full-scale plants with different packing materials.

Meanwhile, inoculation sources will also affect the species of bioaerosol emissions. As shown in Table 1, when the inoculation sources are activated sludge or compost, there is a production of multiple bioaerosols, while using a pure culture of microorganisms will only produce a single specie of bioaerosol. Schlegelmilch et al. (2005) used compost as an inoculation source and demonstrated that bioaerosol emission contained bacteria (mesophilic/thermophilic), molds (mesophilic/thermophilic), and actinomycetes (thermophilic). Saucedo-Lucero et al. (2014) used inoculation obtained from a hydrocarbon polluted site then added chloramphenicol to avoid bacterial growth. They found that the bioaerosol emissions contained only fungi and spores.

Increasing nutrient addition will lead to faster accumulation of biomass, which causes more bioaerosols emissions. Also, the lack of nutrients can lead to the formation of more spores. Vergara-Fernández et al. (2012a) found that an increase in spore emission was observed when the nutrient was consumed, which was due to the fungus’s defense mechanism to adverse conditions.

3.6. Microbial immobilization strategies to reduce bioaerosols emissions

According to the traditional model of biofiltration shown in Fig. 1, microorganisms will adhere to the surface of the packing materials to immobilize themselves, which will reduce the amount of bioaerosol emissions. Some microbial immobilization strategies are illustrated in Table 1. In the study by Wang et al. (2018), phenicol was added to avoid bacterial growth. They found that the bioaerosol concentration decreased by 70% when phenicol was added. In the study by Sather and Satterthwaite (1996), microorganisms were immobilized in perlite and found that the bacterial bioaerosol concentration decreased by 90% compared to the control group. In the study by Saucedo-Lucero et al. (2014), microorganisms were immobilized in perlite and found that the fungal bioaerosol concentration decreased by 85% compared to the control group. These results indicate that microbial immobilization strategies can effectively reduce bioaerosol emissions.
materials and exchange substances with the VOCs-containing airflow. This process will cause the microorganisms to be carried by the airflow and exit the biofiltration process, resulting in the emission of bioaerosols. For reducing bioaerosols emissions from biofilter, microbial immobilization strategies can be utilized. Fig. 5A is the schematic diagram of the microbial immobilization methods. Immobilization microbial technology refers to the use of physical or chemical methods to locate free microorganisms in a limited space, but also to ensure the microbial activity and repeated utilization. Due to its high microbial density, low microbial loss and high reaction speed, immobilization technology has been applied to waste gas treatment since the 1990s (Paje et al., 1998; Miyake-Nakayama et al., 2006).

The use of microbial immobilization strategies, especially the embedding method (Fig. 5B), can effectively reduce the contact between microorganisms and airflow. This can reduce the carrying of microorganisms by the airflow, leading to a reduction in bioaerosol emissions. Although there have been studies on the application of the embedding method for processing VOCs in biofiltration, few studies have been conducted on their bioaerosol emissions. The application of embedding technology is very promising for biofiltration. In principle, embedding can not only improve the performance of biofiltration but can also reduce the emission of bioaerosols.

4. Bioaerosols emissions control technology

4.1. Characteristics of different control technologies

Several technologies have been studied to control bioaerosols. Ultraviolet light (UV–C) with a wavelength of 200–280 nm is an established means of disinfection. The wavelength of this band will (approximately 254 nm) cause direct damage to the microbes’ DNA, thereby inactivating them. UV has been widely used for disinfection in the public health field (hospitals, health care facilities, public shelters), the food industry and the pharmaceutical industry as an environmentally friendly technology (Lee, 2011; Begum et al., 2009). O3 and H2O2 are usually acting as strong oxidizing agents and biocide to inactivate microorganisms. They are more and more widely accepted as eco-friendly technologies and widely applied in the healthcare sector and food factories (Brodowska et al., 2017; Masotti et al., 2019).

Some new technologies have emerged to control airborne microorganisms in recent years. Microwave (MW) is used to inactivate microorganisms by using electromagnetic wave radiation on bioaerosols in a short time, while it can result in the release of endotoxins (Wang et al., 2019b). Plasma technology is the ionization of gas to produce charged ionized gaseous materials. These substances have high energy and can inactivate microorganisms quickly. Photocatalysis disinfection (PCD) relies on the generation of the free electrons and electron holes through light irradiation of the catalyst. These substances are highly oxidizing and can destroy cell membranes of bacteria and the proteins of viruses, even their RNA and DNA.

According to the literature reports and the characteristics of these control technologies, Table 4 presents and evaluates these technologies for inactivating bioaerosols. To summarise, UV, H2O2, and O3 are accepted for its low energy consumption and high efficiency in application. While microwave and plasma are not used in up-scaled commercial applications due to the production of by-products and the wear and energy consumption of equipment. PCD has high application prospects due to high inactivation efficiency and few secondary pollution. More researches are still needed to support and evaluate the practical application of relevant technologies in bioaerosol emissions from biofilters.

There have been some studies using related technologies to control bioaerosols from biofilters. Wang et al. (2009) developed a combined process of UV-biofiltration. The results demonstrated that UV as a pretreatment method could effectively reduce the emission of bioaerosol. Saucedo-Lucero et al. (2014) investigated the post-treatment photoreactor to control spore emission from a biofilter, which confirmed that spore deactivation efficiency of 98% was obtained for the photolytic and photocatalytic post-treatment processes. Valdez-Castillo et al. (2019) used the PCD as post-treatment on the bioaerosol emissions from biofilters. The results showed that the inactivation efficiency of bioaerosol could achieve as high as 70% with an active catalyst. These studies have demonstrated the potential of control technologies to reduce bioaerosol emissions from bioreactors.

4.2. Comparison of energy consumption and performance of different control technologies

In the case of inactivation technologies, technologies including UV, microwave, PCD, and plasma consume electrical energy and convert it into other forms of energy that act on bioaerosols. Table 5 summarizes the inactivation efficiency and energy consumption of the various control technologies mentioned above. The energy consumption of H2O2 is converted according to the amount and price of H2O2, which is converted into the required money and equivalent to the consumption of electricity. O3 energy consumption is estimated according to the parameters of the generator model and dosage.

To evaluate the inactivation performance of different technologies on bioaerosol, the EE/O calculation was used in this study to characterize the energy efficiency of the technologies according to the following equation (Xie et al., 2017; Chen et al., 2019).

\[ EE/O = \frac{0 - \frac{P \cdot t}{V \cdot \log \left( \frac{C_t}{C_0} \right)}}{t} \]

where EE/O is the energy required to inactivate bioaerosol by one order. J m⁻³; P is the power of the device, W; t is the reaction time, s; V is the volume of the bioaerosols, m³; C₀ and Cₜ are the concentrations of bioaerosols at the beginning and at a given time t, respectively, CFU m⁻³.

It can be seen from Table 5 that UV, microwave, PCD, and plasma can inactivate microorganisms in a short time, but the device consumes much energy. Especially for the microwave consumption exceeds 10⁷ J m⁻³. Chemical fogging (H2O2) and O3 inactivation are less effective than other techniques but present long term inactivation effects.

Fig. 6 shows the EE/O ratio of bioaerosols inactivation obtained with different control technologies. Microwave has the highest energy consumption. While chemical fogging (H2O2) and O3 consumption are at a low level of all the technologies. According to the literature survey of bioaerosols inactivation, plasma, chemical fogging (H2O2) and O3 are more suitable for the application of large-scale inactivation of bioaerosols. For treating the bioaerosol-containing gas emitted during biofiltration, the gas can be introduced into the inactivation equipment for treatment or be passed through the gas absorption liquid containing chemical disinfection reagents.

5. Conclusion and prospects

Biofilters are often inoculated by activated sludge and compost, which would contain a large number of pathogenic bacteria and
Fig. 5. A. Schematic diagram of microbial immobilization: (a) Combination method; (b) Cross-linking method; (c) Grid embedding method; (d) Microencapsulation method. B. Formation and emission of bioaerosol in the application of embedding in the biofiltration.
viruses. Therefore, bioaerosol emissions from biofilters are generally higher than background values, which would cause lung disease and inflammation, and pose a great potential threat to human health. Additionally, many factors influence the emissions of bioaerosols during biofiltration. High biomass accumulation results in higher concentrations of bioaerosol emissions. Increasing gas velocity will raise the bioaerosol emissions first and then decrease the concentrations due to the shearing force and dilution effect. High moisture content and temperatures will reduce bioaerosol emissions and have an impact on bioaerosol species. As for bioaerosol control technologies, UV, H₂O₂, and O₃ are applicable for its low energy consumption and high inactivation efficiency. Also, PCD is a very promising technology for controlling bioaerosol because of the less secondary pollution generation and high inactivation efficiency. Moreover, more comprehensive techniques should be used to monitor the bioaerosols rather than just relying on the inactivation monitor. Not only living microorganisms, but also microbial fragments can cause damage to the human body. The monitoring and counting techniques of bioaerosols are necessary for homogenization, and these can be taken into account to establish legislation. New methods of characterization and health risk assessment are also needed due to health effects is the function of the species of the

Table 4
Comparison of different bioaerosol control technologies.

| Technology | Effect | Energy consumption | Secondary pollution | Stability | Applicability |
|------------|--------|---------------------|---------------------|-----------|---------------|
| UV         | ●      | ○                   | ●                   | ●         | ●             |
| PCD        | ●      | ○                   | ●                   | ○         | ○             |
| MV         | ●      | ●                   | ●                   | ○         | ○             |
| Plasma     | ●      | ○                   | ●                   | ○         | ○             |
| O₃         | ●      | ○                   | ●                   | ○         | ○             |
| H₂O₂       | ●      | ○                   | ●                   | ○         | ○             |
| Filtration | ●      | ○                   | ●                   | ○         | ○             |

●: High level; ○: Middle level; ●: Low level.

Table 5
Comparison of energy consumption and the effects of different bioaerosol control technologies.

| Control technologies | Bacteria | Conditions | Inactivation efficiency | EE/O (J m⁻³) | reference |
|----------------------|----------|------------|-------------------------|--------------|-----------|
| UVGI                 | B. subtilis | 10 W (33.1 W m⁻²) | 12 J m⁻² for 1 lg | 4.5 | Ryan et al. (2010) |
|                     | B. subtilis | 15 W (0.85 W m⁻²) | 150 s for 1 lg | 16423.36 | King et al. (2011) |
|                     | B. subtilis | 600 W; V = 2 m³ | 1 s for 0.82 lg | 365.85 | Wang (2012) |
|                     | E. coli | 30 W; V = 1.8 L | 10 s for 1.52 lg | 86979.16 | Wang et al. (2019a) |
| PCD                 | E. coli | 16 W TiO₂; V = 1.9 L | 14 s for 0.3 lg | 392982.46 | Modesto et al. (2013) |
|                     | E. coli | 32 W; V = 1.8 L | 18 s for 2.7 lg | 118518.52 | Keller et al. (2005) |
|                     | L. pneumophila | 24 W TiO₂; V = 1 L | 1.4 s for 1.15 lg | 29217.39 | Josset et al. (2007) |
|                     | Bacteria and fungi | 30 W TiO₂; V = 3 L | – | – | Paschoalino and Jardim (2008) |
|                     | Bacteria and fungi | V = 210 mL | – | – | Valdez-Castillo et al. (2019) |
| H₂O₂ or O₃         | S. albus | H₂O₂ 90.3 mg m⁻³ | 15 min for 3 lg | 788.08 | Tan et al. (2005) |
| Natural bacteria    | 3% H₂O₂ 20 ml m⁻³ | 60 min for 1.35 lg | 11636.37 | Jiang et al. (2004) |
| Natural bacteria    | O₃ 44.81 mg m⁻³ | 60 min for 1.02 lg | 3953.82 | Xiang et al. (2012) |
|                     | O₃ 44.50 mg m⁻³ | 60 min for 1.10 lg | 3640.91 | |
|                     | O₃ 44.15 mg m⁻³ | 60 min for 1.01 lg | 3934.16 | |
|                     | O₃ 43.95 mg m⁻³ | 60 min for 1.7 lg | 2326.76 | |
| Plasma              | S. albus | – | – | 3197.97 | Park and Hwang, 2013 |
|                     | MS2      | 21 W; V = 1.97 L | 0.69 s for 2.3 lg | 3197.97 | Xia et al. (2019) |
|                     | E. coli | 100 W; V = 250 L | 10 s for 5 lg | 800 | Gallagher et al. (2007) |
|                     | E. coli | 100 W; V = 250 L | 10 s for 3.5 lg | 1142.86 | Vaze et al. (2010) |
|                     | B. subtilis | 24 W | 0.12 s for 1.8 lg | 2326.76 | Wu (2013) |
| MV                  | E. coli | 700 W; V = 1.6 L | 20 s for 4.15 lg | 2108433.73 | Wang et al. (2018) |
|                     | B. subtilis | 700 W; V = 21 L | 1.7 min for 0.55 lg | 6181818.18 | Wu and Yao. (2010) |

Fig. 6. Comparison of EE/O consumption of inactivating bioaerosols by different technologies (where H₂O₂ and O₃ are converted into equivalent electrical energy according to their dosage).
bioaerosols emitted, the physiology of cells (dead, injured, live), the content of endotoxin and mycotoxin, viruses, etc.

Credit Author Statement

Xu-Rui Hu: Writing-Original draft preparation. Meng-Fei Han: Writing for Influencing factors. Can Wang: Writing- Reviewing and Editing. Nan-Yang Yang: Data collection and plotting. Yong-Chao Wang: Drawing Tables. Er-Hong Duan: Conceptualization, Supervision. Hsing-Cheng Hsi: Writing for Microbial immobilization. Ji-Guang Deng: Writing for control technologies.

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.

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References

Alonso, C., Suidan, M.T., Kim, B.R., Kim, B.J., 1998. Dynamic mathematical model for the biodegradation of vocs in a biofilter: biomass accumulation study. Environ. Sci. Technol. 32, 3118–3123.

Alvarez-Hornos, F.J., Caballol, C., Martinez-Soria, V., Martin, M., Marzal, P., Penya-Roja, J.M., 2008. Biofiltration of ethylbenzene vapours: influence of the packing material. Bioresour. Technol. 99, 269–276.

Balloy, V., Chignard, M., 2009. The innate immune response to Aspergillus fumigatus. Microbiol. Infect. 11, 919–927.

Bauer, H., Fuerhacker, M., Zibuschka, F., Schmid, H., Puxbaum, H., 2002. Bacteria and viruses in the content of endotoxin and mycotoxin, viruses, etc. in municipal wastewater by ozone generated in arrays of microchannel plasma. J. Phys. D Appl. Phys. 35, D25501.

Birch, R.B., Stewart, W.E., Lightfoot, E.N., 1960. Transport Phenomena. John Wiley & Sons, Inc, New York.

Bonfait, L., Marchand, G., Veillette, M., MBareche, H., Dubuis, M.E., Pépin, C., Cloutier, Y., Bernard, Y., Duchaine, C., 2017. Workers’ exposure to bioaerosols from three different types of composting facilities. J. Occup. Environ. Hyg. 14, 815–822.

Breza-Boruta, B., 2010. The assessment of airborne bacterial and fumigation contamination emitted by a municipal landfill site in Northern Poland. Atmos. Pollut. Res. 7, 1043–1052.

Brodowska, A.J., Nowak, A., Smigielski, K., 2017. Ozone in the food industry: principles of ozone treatment, mechanism of action, and applications: an overview. Crit. Rev. Food Sci. Nutr. 58, 2178–2201.

Burge, H., 1990. Bioaerosols: prevalence and health effects in the indoor environment. In: J. Food Microbiol. 129, 74–77.

Cai, L., Zhang, T., 2013. Detecting human bacterial pathogens in wastewater treatment plants by a high-throughput shotgun sequencing technique. Environ. Sci. Technol. 47, 5433–5441.

Casati, S., Conza, L., Bruschi, G., Schmid, H., Puxbaum, H., 2002. Bacteria and viruses in the content of endotoxin and mycotoxin, viruses, etc. in municipal wastewater by ozone generated in arrays of microchannel plasma. J. Phys. D Appl. Phys. 35, D25501.

Chen, M., Wang, C., Wang, Y.C., Meng, X.Y., Chen, Z.F., Zhang, W.Q., Tanc, G., 2019. Primary biological aerosol particles in the atmosphere: a review. Tellus Ser. B Chem. Meteorol. Geophys. 64, 15598.

Devlinny, J.S., MacCabe, W., Webster, T.S., 2019. Biofiltration for Air Pollution Control. CRC. Pr. Inc.

Ding, Y.Q., He, L., Zhang, Q.L., Huang, Z.X., Che, X.Y., Hou, J.L., et al., 2004. Organ distribution of severe acute respiratory syndrome (SARS) associated coronavirus (SARS-CoV) in SARS patients: implications for pathogenesis and virus transmission pathways. J. Pathol. 203 (2), 622–630.

Dong, S.K., Li, J., Kim, M.H., Cho, J., Park, S.J., Nguyen, T.H., Eden, J.G., 2018. Deactivation of Legionella pneumophila in municipal wastewater by ozone generated in arrays of microchannel plasma. J. Phys. D Appl. Phys. 51, 25501.

Douwes, J., Thorne, P., Pearce, N., Heederik, D., 2003. Bioaerosol health effects and exposure assessment: progress and prospects. Ann. Occup. Hyg. 47, 187–200.

Esquivel-González, S., Aizpurua, A., Patrón-Soberano, A., Arriaga, S., 2017. Characterization of bioaerosol emissions from two biofilters during treatment of toluene vapours using epifluorescence microscopy. Int. Biodeterior. Biodegrad. 123, 78–86.

Fracchia, L., Pietronave, S., Rinaldi, M., Martinotti, M.G., 2006. Site-related airborne biological hazard and seasonal variations in two wastewater treatment plants. Water Res. 40, 1985–1994.

Gallagher, M.J., Vaze, N., Gangoli, S., Vasilets, V.N., Gutsol, A.F., Milovanova, T.N., Anandhan, S., Murasko, D.M., Fridman, A.A., 2007. Rapid inactivation of airborne bacteria using atmospheric pressure dielectric barrier discharge grating discharging. IEEE Trans. Plasma Sci. 35, 1501–1510.

Ghosh, B., Lal, H., Srivastava, A., 2015. Review of bioaerosols in indoor environment with special reference to sampling, analysis and control mechanisms. Environ. Int. 85, 234–272.

Giraud, M., Ramirez, A.A., Buena, G., Michaud, H., 2011. Biofiltration of methane at low concentrations representative of the piggery industry — influence of the methane and nitrogen concentrations. Chem. Eng. J. 168, 151–158.

Gün, R.L., 2020. Microbial aerosols: sources, properties, health effects, exposure assessment — a review. KONA Powder Part. J. 37, 64–84, 2020005.

Gromeestijn, J.W., Krakman, N.J.R., 2005. Recent developments in biological waste gas purification in Europe. Chem. Eng. J. 113, 85–91.

Husman, T., 1996. Health effects of indoor-air microorganisms. Scand. J. Work. Environ. Health 22, 5–13.

Ibangs, I.E., Fletcher, A.A., Noakes, C.J., King, M.F., Steinberg, D., 2018. Pilot-scale biorefiltration at a material recovery facility: the impact on biocontrol. Waste Manag. 80, 154–167.

Ivanpoulov, R., Cox, H.H.J., Deshusses, M.A., Schroeder, E.D., 2005. Literature review of air pollution control biofilters and biotrickling filters for odor and volatile organic compound removal. Environ. Prog. 24, 254–267.

Jang, X.B., Ma, C., Lu, X.B., Wang, Z.G., Li, Y.J., Gu, D.D., 2004. Six kinds of indoor air disinfection methods: comparison of their effects. Chinese Journal of Nosocomiology (China) 14, 62–63.

Jesiot, S., Taranto, J., Keller, N., Valérie, K., Lett, M.C., Ledoux, M.J., Bonnet, V., Rougeau, S., 2007. UV-A photocatalytic treatment of high flow rate air contaminated with Legionella pneumophila. Catal. Today. 129, 215–222.

Keller, V., Keller, N., Ledoux, M.J., Lett, M.C., 2005. Biological agent inactivation in a flowing air stream by photo-catalysis. Chem. Commun. 2918–2920.

Kennes, C., 2012. Biotechniques for air pollution control and bioenergy. J. Chem. Technol. Biotechnol. 87, 723–724.

Kim, D., Cai, Z., Sortal, C.A., Shin, H., Knaebel, K., 2007. Integrated treatment scheme for odor and volatile organic compound removal. Environ. Prog. 26, 225–227.

Kumar, V., Thiel, W.R., 2008. Bioaerosols — sources and control measures. Int. J. Hyg. Environ. Health 211, 299–307.

Lagé, J.P., 2001. The pathology of Aspergillus fumigatus. Trends Microbiol. 9, 542–589.

Lee, B.U., 2011. Life comes from the air: a short review on bioaerosol control. Aerosol Air Qual. Res. 11, 921–927.

Lin, T.H., Chang, C.F., Lin, S.T., Tsai, C.T., 2016. Effects of small-size suspended solids on the emission of Escherichia coli from the collection process of wastewater treatment. Aerosol Air Qual. Res. 16, 2208–2215.

Liu, H., Zhang, X., Zhang, H., Yao, X.W., Zhou, M., Wang, J.Q., 2018. Effect of air pollution on the total bacteria and pathogenic bacteria in different sizes of particulate matter. Environ. Pollut. 233, 481–491.

Martens, W., Martinec, M., Zapirain, R., Stark, M., Hartung, E., Palmgren, U., 2001. Reduction potential of microbial, odor and ammonia emissions from a pig facility by biofilters. Int. J. Hyg. Environ. Health 203, 335–345.

Masotti, F., Cattaneo, S., Stuknyt, M., Noni, I.D., 2019. Airborne contamination in the food industry: an update on monitoring and disinfection techniques of air. Trends Food Sci. Technol. 90, 147–156.

Menetrez, M.Y., Foarde, K.K., Esch, R.K., Schwartz, T.D., Dean, T.R., Hays, M.D., Cho, S.H., Betancourt, D.A., Moorea, S.A., 2009. An evaluation of indoor and outdoor biological particulate matter. Atmos. Environ. 43, 5476–5483.
Sanchez-Monedero, M.A., Stentiford, E.I., Mondini, C., 2003. Biodegradation of dichloromethane by the polyvinyl alcohol-immobilized methyloptrophic bacterium Ralstonia metallidurans PD11. Appl. Microbiol. Biotechnol. 70, 625–630.

Modesto, O., Hammer, P., Pupo Nogueira, R.F., 2013. Gas phase photocatalytic bacteria inactivation using metal modified TiO2 catalysts. J. Photochem. Photobiol. Chem. 253, 38–44.

Mudliar, S., Giri, B., Padolek, K., Satpute, D., Dixit, R., Bhatt, P., Pandey, R., Juwarkar, A., Vaidya, A., 2010. Bioreactors for treatment of VOCs and odours — a review. J. Environ. Manag. 91, 1039–1054.

Nicolella, C., DiFelice, R., Rosatti, M., 1996. An experimental model of biofilm detachment in liquid fluidized bed biological reactors. Biotechnol. Bioeng. 51, 713–719.

Otawa, K., Lee, S.H., Yamazoe, A., Onuki, M., Satoh, H., Mino, T., 2007. Abundance, diversity, and dynamics of viruses on microorganisms in activated sludge processes. Microb. Ecol. 53, 143–152.

Ottinger, S.P.P., Konings, J.H.G., 1991. Emission of microorganisms from biofilters. Bioprocess Eng. 7, 85–96.

Paje, M.L., Marks, P., Couperwhite, I., 1998. Degradation of benzene by a Rhodococcus sp. using immobilized cell systems. World J. Microbiol. Biotechnol. 14, 675–680.

Park, C.W., Hwang, J., 2013. Susceptibility constants of airborne bacteria to dielectric barrier discharge for antibacterial performance evaluation. J. Hazard Mater. 244, 430–4303.

Pearson, C., Littlewood, E., Douglas, P., Robertson, S., Gant, T.W., Hansell, A.L., 2015. The potential to reduce emissions of airborne microorganisms by means of biological filtration of hydrophobic VOCs. J. Chem. Technol. Biotechnol. 87, 778–784.

Sharma, H., Khanna, H., 2017. Bioaerosol emission control in a fungal biofilter process for chlorobenzene treatment. J. Air Waste Manag. Assoc. 59, 405–410.

Wang, C., Zhang, Z.W., Liu, H., 2019b. Microwave-induced release and degradation of airborne endotoxins from Escherichia coli bioaerosol. J. Mater. Hazard. 36, 27–33.

Wang, Y., 2012. Study on In-Duct Ultraviolet Germicidal Irradiation (UVGI) Dynamic Air Disinfection Technology (Master’s Degree Thesis). Tianjin University, Tianjin, China.

Wang, Y.C., Fu, Y., Wang, C., Wen, N.J., 2018. Dissimilar emission characteristics between bioaerosol and suspended particles from gaseous biofilters and bioaerosol health risk evaluation. Aerosol Air Qual. Res. 18, 1874–1885.

Wang, Y.Z., Wang, C., Song, L., 2019c. Distribution of antibiotic resistance genes and bacteria from six atmospheric environments: exposure risk to human. Sci. Total Environ. 694, 133750.

Wang, C., Xi, J.Y., Hu, H.Y., 2009. Reduction of toxic products and bioaerosol emission of a combined ultraviolet-biofilter process for chlorobenzene treatment. J. Air Waste Manag. Assoc. 59, 405–410.