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# Dissimilar Emission Characteristics between Bioaerosol and Suspended Particles from Gaseous Biofilters and Bioaerosol Health Risk Evaluation

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## ABSTRACT

Biofiltration is a common technology for treating volatile organic compounds (VOCs); however, bioaerosols may be emitted in the gas flow, indicating a potential risk to human health. In this study, we analyzed the emission characteristics of bioaerosol and suspended particles (mainly nonbiological particles) emitted from biofilters and their health risk at different gas velocities and temperatures and with different amounts of moisture in the packing bed. Results showed that a high gas velocity enabled easy transport of microbes from the carriers. The maximum bacterial aerosol outlet concentration was 223 CFU $m^{-3}$ at 50°C, although the fungal aerosol concentration decreased at temperatures above 25°C. The peak bacterial concentration was 349 CFU $m^{-3}$, with a moisture content of 70%, whereas the highest fungi concentration was nearly 267 CFU $m^{-3}$, with a moisture content of 40%. The bioaerosol concentrations also changed with the experimental conditions: A high gas velocity, low temperature, and high moisture content favored the emission of fine particles; however, changes in the concentration and size distribution of coarse particles were not obvious. The relationship between bioaerosols and suspended particle emissions demonstrates that biofilters are a source of bioaerosol emissions despite the removal of nonbiological suspended particles due to filtration. The health risk evaluation indicates that bioaerosol emissions from biofilters pose the highest risk of infection via inhalation to adult males.

***Keywords:*** Biofilter; Bioaerosol; Suspended particle; Emission characteristic; Health risk assessment.

## INTRODUCTION

Bioaerosols are the suspension of airborne particles that are living and those originating from living organisms, including pollen, fungal spores, bacteria, viruses, animal dander, and mite-associated fragments (ACGIH, 1999; Chow *et al.*, 2015; Tarigan *et al.*, 2017). These particles are very small and range in size from less than 1 μm to 100 μm (Yu, 2002). They can either exist as individual entities or form aggregates of biological structures and also attached to soil dust particles, water droplets and chemical constituents of aerosols (Szymczak and Gorny, 2010; Agarwal *et al.*, 2016), being able to affect human health by causing infectious diseases, acute toxic reactions, allergies and so on (Ghosh *et al.*, 2015; Wen *et al.*, 2017).

Biofiltration is a common technology to treat volatile organic compounds (VOCs), using microorganisms inside biofilters to degrade the target contaminants (Devinny *et al.*, 1999; Deshusses and Johnson, 2000). For full-scale biofilters, sludge (from wastewater treatment plants) or municipal wastes are often used as inoculation source for organisms. A variety of harmful and infectious organisms have been found inside the sludge (Lin *et al.*, 2016) and municipal wastes (Vilavert *et al.*, 2009). During biofilters operation, some microorganisms could be carried out forming bioaerosol when gas flow goes through biofilters (Kummer and Thiel, 2008; Wang *et al.*, 2009). Some studies regarded biofilters as a source of bioaerosol emissions (Ottengraf and Konings, 1991), showing potential risk in human health, especially for those occupational exposed to bioaerosols. Therefore, attention should be paid on the bioaerosol emissions from biofilters.

A few studies have been performed regarding the bioaerosol emitted from biofilters in recent years. Esquivel-Gonzalez *et al.* (2017) reported that bioaerosol emitted concentrations from biofilters during the treatment of toluene vapors were between $6.4 \times 10^5$ and $1.3 \times 10^8$ cells $m^{-3}_{air}$ compared with the bioaerosol concentration in ambient air, which was $3.0 \times 10^7 \pm 7 \times 10^6$ cells $m^{-3}_{air}$. Wang *et al.* (2009) examined the bioaerosol emissions from the biofilter using ultraviolet photodegradation as pretreatment. They found that the ozone produced by ultraviolet photodegradation decreased the concentration of bioaerosol from $1.38 \times 10^3$ CFU $m^{-3}$ (without pretreatment) to 60 CFU $m^{-3}$ (with

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pretreatment), nearly the same as the background level of 40 CFU $m^{-3}$. Saucedo-Lucero *et al.* (2014) reported that biofilter irrigation every 3 days supported fungal spore emissions at concentrations ranging from $2.4 \times 10^3$ to $9.0 \times 10^4$ CFU $m^{-3}$ in a fungal biofilter-photoreactor hybrid unit. Tamer *et al.* (2014) analyzed the morphology of bioaerosol from composting using scanning electron microscopy. The results showed that the particles were released mainly as small (< 1 μm) single, spherical cells, followed by larger (> 1 μm) single cells, with aggregates occurring in smaller proportions. All these findings indicate that significant bioaerosol concentrations have been detected in the outlet of biofilters. However, little information has been reported about the effects of biofilters operating parameters on bioaerosol emissions characteristic. The nonbiological particles, such as suspended particles, were ignored when bioaerosol emitted from biofilters was characterized. The dissimilar emission characteristics of bioaerosol and suspended particles emitted from a biofilter has not been fully discussed in previous studies. Also, the health risk need to be assessed during the bioaerosol emissions from a gaseous biofilters under different operating conditions.

In this study, a biofilter treating gaseous toluene was selected as experimental device. The inlet toluene concentration was 160–650 mg $m^{-3}$ with the air flow rate 0.2–0.8 $m^3$ $h^{-1}$, empty bed retention time and loading rate were calculated as 6.75–27 s and 86.6 g $m^{-3}$ $h^{-1}$. Both bioaerosol (including bacteria and fungi) and suspended particle (mainly non-biological particle) emissions were investigated under different operating conditions. Furthermore, the relationship between the bioaerosol and suspended particle was analyzed. Health risk assessment of emitted bioaerosol was evaluated using mathematical model under different operating conditions.

## METHODS

### *Microbe Sampling and Acclimatization*

Activated sludge was sampled in the aeration tank of Tianjin Jingu wastewater treatment plant (Tianjin, China). 10 ml gaseous toluene was injected to 4 L activated sludge for acclimatization every 2 days in the first week and the injection volume was increased to 20 ml every 2 days in second week. During the acclimatization, 8 h aeration was applied for sludge growth in each day. The component and concentration of nutrient solution were showed in Table 1. After 2 weeks of acclimatization, the pearlite was mixed with sludge to form biofilms.

### *Biofilter Set-up and Operating Conditions*

A biofilter was constructed using stainless steel with an internal diameter of 8 cm and filled with two layers packing, namely, the upper layer was 30 cm perlite and the lower was 3 cm ceramic. The total volume of the biofilter layer was 1.5 L. The schematic diagram of the biofilter was showed in Fig. 1. In order to stabilize the operation of the biofilter system, preoperation was carried out for 5 d under 0.15 mL $h^{-1}$ toluene injection with air flow rate of 0.2 $m^3$ $h^{-1}$, under which the empty tower velocity was 40 m $h^{-1}$. 200 ml nutrient medium was sprayed to biofilters for microbial growth every 12 h. After preoperation, the experiments were conducted. The inlet toluene concentration was 160–650 mg $m^{-3}$ with the air flow rate 0.2–0.8 $m^3$ $h^{-1}$, empty bed retention time and loading rate were calculated as 6.75–27 s and 86.6 g $m^{-3}$ $h^{-1}$. The operating conditions including gas velocity (m $h^{-1}$), gas temperature (°C) and packing bed moisture content (%) were studied for bioaerosol emissions. During sampling, the gas velocity, the gas temperature and the moisture content in the packing bed were set as 40–160 m $h^{-1}$, 20–70°C and 20–90%, respectively. All parameters of operating conditions were summarized in Table 2 and more detailed information about the operating conditions could be found in Supplementary Material (See Text S1).

### *Sampling Methods*

*Bioaerosol*

A 6-stage Andersen impactor sampler was used to collect culturable bacterial and fungal aerosol with different size ranges. The range of aerodynamic diameter at each stage was: ≥ 7.0 μm (stage 1), 7.0–4.7 μm (stage 2), 4.7–3.3 μm (stage 3), 3.3–2.1 μm (stage 4), 2.1–1.1 μm (stage 5) and 1.1–0.65 μm (stage 6) (Xu and Yao, 2013). The bioaerosol was collected at a flow rate of 28.3 L $min^{-1}$ and was run for 10 min at a height of 1.5 m above the ground level. The biosampler was sterilized using a 75% ethanol solution before sampling. After sterilization, six glass petri dishes of 90 mm in diameter were placed in the impactor sampler, which included suitable medium for microbial growth. The Nutrient Agar (3 g beef extract, 10 g peptone, 5 g sodium chloride, 15 g agar, 1000 mL distilled water) and Rose Bengal Medium (5 g peptone, 10 g glucose, 1 g potassium phosphate monobasic, 0.5 g magnesium sulfate, 20 g agar, 100 mL 1/3000 rose bengal solution, 1000 mL distilled water, 0.3 g Chloramphenicol) were used to culture the bacteria and fungi, respectively. Three replicates were taken at each single sampling. The bacteria samples were incubated at 37°C for 48 h, whereas the fungi samples

**Table 1.** The component and concentration of nutrient solution.

| Component | Concentration (g $L^{-1}$) | Component | Concentration (g $L^{-1}$) |
|---|---|---|---|
| $Na_2HPO_4 \cdot 12H_2O$ | 7 | $Ca(NO_3)_2 \cdot 4H_2O$ | 0.6 |
| $KH_2PO_4$ | 2 | $CuSO_4 \cdot 5H_2O$ | 0.04 |
| $(NH_4)_2SO_4$ | 2.5 | $FeSO_4 \cdot 7H_2O$ | 0.2 |
| $MgSO_4 \cdot 7H_2O$ | 0.2 | $ZnSO_4 \cdot 7H_2O$ | 0.02 |
| $H_3BO_3$ | 0.003 | $MnSO_4 \cdot 4H_2O$ | 0.02 |
| $Na_2MoO_4 \cdot H_2O$ | 0.004 | | |

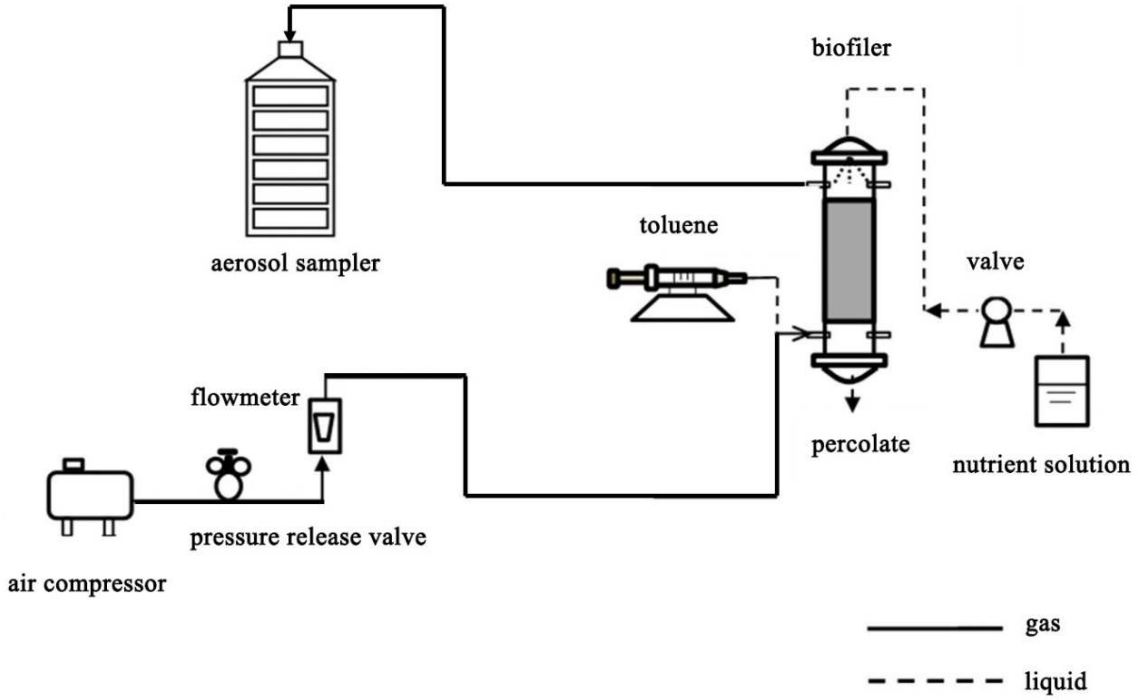


**Fig. 1.** The schematic diagram of the biofilter in this study.

**Table 2.** The detailed information of the operating conditions

| | Variables | Operating Conditions |
|---|---|---|
| Controlling factor | toluene concentration | 160–650 mg $m^{-3}$ |
| | air flow rate | 0.2–0.8 $m^3 h^{-1}$ |
| | empty bed retention time | 6.75–27 s |
| | inlet loading rate | 86.6 g $m^{-3} h^{-1}$ |
| | nutrient medium spray rate | 1.75 mL $s^{-1}$ |
| Impacting factor | gas velocity | 40–160 m $h^{-1}$ |
| | temperature | 20–70°C |
| | moisture contents | 20–90% |

were incubated at 25°C for 72 h in incubator (Li *et al.*, 2011; Gao *et al.*, 2015). After incubation, the colonies were counted using the positive hole correction for colony overlapping (Andersen, 1958). The number of colony forming units (CFUs) recovered from each sample was finally expressed in CFU $m^{-3}$. The concentration of bioaerosol was calculated according to the Eq. (1):

$$Concentration\ (CFU\ m^{-3}) = \frac{1000N}{Qt} \quad (1)$$

where $N$ is the number of colonies on the plates, $Q$ is the flow rate of sampling pump (L $min^{-1}$) and $t$ is the sampling time (min).

*Particles*

The number of particles was simultaneously determined by an airborne particle counter DT-9880. There was a proportional relationship between scattering flux and particle size under illumination. Therefore, when the flow rate and time of sampling was defined, the instrument would be able to measure the total number of particles, which was greater than a predetermined value within a given volume. The particles can also be categorized into six channels according to the particles size: 0.3 μm (stage 1), 0.5 μm (stage 2), 1.0 μm (stage 3), 2.5 μm (stage 4), 5.0 μm (stage 5) and 10 μm (stage 6). It is worth noting that the meteorological data, including temperature and relative humidity, were concurrently recorded by an automatic meteorological station during the sampling period. The average count was recorded according to the number of particles displayed on airborne particle counter.

***Morphology of the Bioaerosol***

In this study, the morphology of colonies, including color, size, shape and aggregation status, were observed by naked-eye.

***Mathematical Model for Bioaerosol Emissions Assessment***

*Bioaerosol Exposure Dose Model*

Bioaerosol could be spread and diffused in air and is of

migration characteristic. It is generally considered that respiratory inhalation and skin contact are two primary accesses to human. In this study, average exposure dose assessment of a respiratory inhalation model and a skin contact model were calculated using Eqs. (2)–(3), retrieved from the United States Environmental Protection Agency (USEPA) *Exposure Factors Handbook* (USEPA, 2011).

$$ADD_{inhalation} = \frac{c \times IR \times EF \times ET_{inhalation}}{BW \times AT} \quad (2)$$

$$ADD_{skin} = \frac{c \times S_A \times P_C \times EF \times ET_{skin} \times 24}{BW \times AT} \quad (3)$$

where $ADD_{inhalation}$ represents the average exposure dose of the respiratory system (CFU $d^{-1}$ $kg^{-1}$); $c$ is the average bioaerosol concentration (CFU $m^{-3}$); $IR$ is the inhalation rate ($m^{-3}$ d); $EF$ is the exposed frequency (d $a^{-1}$); $ET$ is the respiratory inhalation exposure time (a); $ADD_{skin}$ is the average exposure dose of skin contact (CFU $d^{-1}$ $kg^{-1}$); $S_A$ is the surface area of skin contact ($m^2$); $P_C$ is the skin permeability (m $h^{-1}$); $ET_{skin}$ is the skin contact exposure time (a); $BW$ is the body weight of exposed people (kg); and $AT$ is the average life expectancy (d). According to the highest risk of evaluation objections, the exposed sensitive population in our study was divided into 3 groups: children, adult males, and adult females. Exposure dose was calculated through the Eqs. (2)–(3) using the average emitted bioaerosol concentration. Other values of selected parameters were listed in Table 3.

*Bioaerosol Health Risk Assessment Model*

Hazard index (*HI*) was used to evaluate the health risk in this study. Since bioaerosol is noncarcinogenic, its health risk to exposed population was then assessed and shown mathematically as a probabilistic risk profile (USEPA, 2011) as Eqs. (4)–(5).

$$HQ = \frac{ADD}{RfD} \quad (4)$$

$$HI = \sum HQ_i \quad (5)$$

where $HQ$ is the quotient of risk of noncarcinogens and expresses the risk of noncarcinogens of single pollutant in each exposure method; $RfD$ is the reference dose (CFU $d^{-1}$ $kg^{-1}$); and $HI$ is the total risk of noncarcinogens of multi-pollutants in multiple exposure methods. When $HQ < 1$ or $HI < 1$, risk is minimal and can be ignored. When $HQ > 1$ or $HI > 1$, the risk of noncarcinogens to exposed people is indicated. $RfD$ was selected as 5000 CFU $m^{-3}$ according to the report that adversely health effects were showed on exposed populations when bioaerosol dose is higher than 5000 CFU $m^{-3}$ (Sigsgaard *et al.*, 1990).

## RESULTS AND DISCUSSION

### *Morphology of the Bioaerosol*

The physical appearance and morphological characteristics of bioaerosol are shown in Fig. S1. In this study, the bioaerosol concentration of the outlet was larger than that of the inlet. More colonies in the dishes of the outlet were observed compared with inlet. However, the morphology of colonies showed no obvious change. The captured bioaerosol were classified as bacterial aerosol and fungal aerosol. The bacterial colonies were milky, round particles with smooth and moist surface or with small protuberances. Colonies were classified as small (< 0.5 cm) and large (0.5–1 cm) colonies according to their diameters, from which the small colonies were more concentrated, while the large colonies were dispersed. The fungal colonies were white, round particles with prominent projections and a "flower-like" structure. Compared with colonies of bacteria, the range of fungal colonies diameter was 0.5–0.7 cm, with a more uniform and discrete distribution.

### *Effects of Gas Velocity on Bioaerosol Emissions*

*Effects of Gas Velocity on Bioaerosol Concentration*

The concentration of bioaerosol under different gas velocities is described in Fig. 2(a). As the gas velocity increased, the outlet bioaerosol concentration (bacterial and fungal aerosol) were first increased and then decreased. When the gas velocity reached to 140 m $h^{-1}$, around 800 CFU $m^{-3}$ of total bioaerosol at the outlet of the biofilter were detected. At this point, the concentration of bacterial and fungal aerosol had reached to the maximum values of 370 CFU $m^{-3}$ and 431 CFU $m^{-3}$, respectively, which were much higher than the background concentration level of 60 CFU $m^{-3}$ (bioaerosol concentration in the surrounding

**Table 3.** Exposure dose calculating parameters of different sensitive population groups.

| Parameters[a] | Units | Values | | |
|---|---|---|---|---|
| | | Children | Adult males | Adult females |
| $IR$ | $m^3$ $d^{-1}$ | 7.6 | 19.02 | 14.17 |
| $ET$ | a | 6 | 24 | |
| $EF$ | d $a^{-1}$ | 180 | | |
| $S_A$ | $m^2$ | 0.115 | 0.215 | |
| $P_C$ | m $h^{-1}$ | 0.001 | | |
| $BW$ | kg | 15.0 | 62.7 | 54.4 |
| $AT$ | d | 12 × 365 | 69.6 × 365 | 73.3 × 365 |

[a] The Values of calculation parameters were retrieved from other references (MHC, 2009; USEPA, 2011; Qiu *et al*., 2012; MEPC, 2013; Liu *et al.*, 2017).

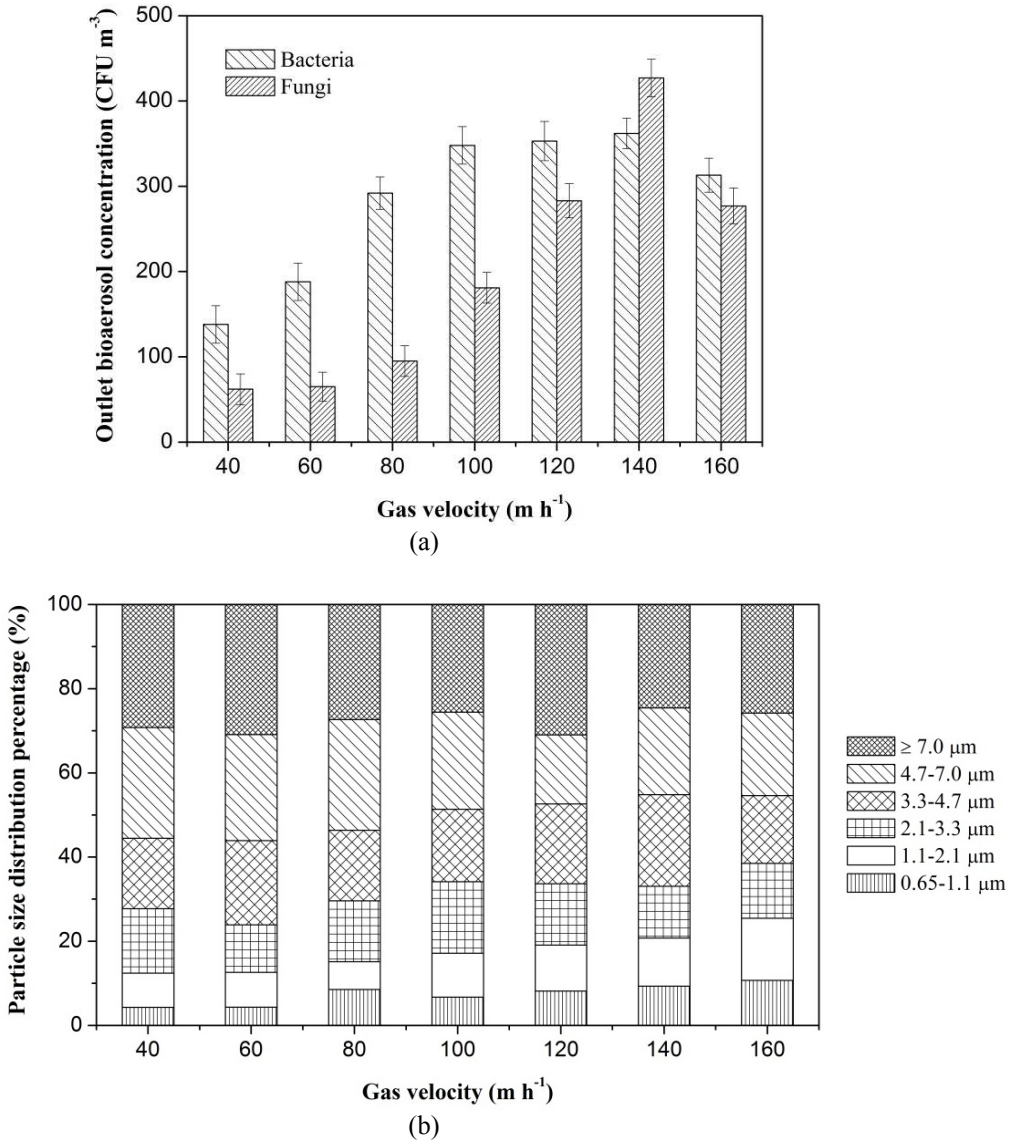


**Fig. 2.** The effect of different gas velocities on bioaerosol emission characteristic: (a) Concentration characteristic (b) Particle size distribution characteristic.

environment). The results showed that within a certain range, the higher gas velocity resulted in stronger shear force on the biofilm insider the biofilter, which made microorganisms easily be brought away from the carriers to form bioaerosol emissions. The enhancement effects of high gas velocity for bioaerosol emissions has also been founded from Lin *et al.* (2016) study, in which bioaerosols concentration increased with the rising aeration rate. However, the bioaerosol concentration began to decrease when the gas velocity reached a certain level. This phenomenon might be concerned with a few microbial fluxes on microbial carrier surface in biofilters as well as the dilution effect of gas emission. On the one hand, high gas velocity is not suitable for microbe aggregation, causing microbe slough off from carriers to the leachate. Besides, rapid gas flow disturbed microbial growth and biodegradation of organic gas, which resulted in the decay of microbes. On the other hand, the decrease of bioaerosol emissions concentration might also be due to a part of dilution effect caused by high gas velocity.

Fig. S2 shows the difference of bioaerosol concentration between inlet and outlet ($C_{outlet} - C_{inlet}$) under different gas velocities in biofilters. The inlet bioaerosol concentration, including bacteria and fungi, was maintained around 60 CFU $m^{-3}$, nearly the same value as the background level. On the contrary, the outlet bioaerosol concentrations were much higher than inlet concentrations, indicating that biofilters were potential sources of bioaerosol emissions.

*Effects of Gas Velocity on Particle Size Distribution*

In this study, the bioaerosol emissions were divided into six stages according to their particle size as measured by a 6-stage Andersen impactor sampler at different velocities (Fig. 2(b)). A wide variety of microorganisms was present in and released from the biofilter. In general, under the different studied velocity conditions, the small size particles

(0.65–2.1 μm) accounted for 55% of the total bioaerosol, while the coarse particles (> 4.7 μm) represented about 20% of the total. This distribution might be explained that large particles are more susceptible to the action of gravity settling (Lloyd *et al.*, 1994) and thus, they deposited in the biofilter; on the other hand, the small particles are more easily brought out by the exhaust gas. Moreover, the total proportion of the fifth (1.1–2.1 μm) and sixth (0.65–1.1 μm) stages gradually decreased from 55% to 50%. Conversely, the proportion of large particles (> 4.7 μm) increased from 12% to 25%. The results indicated that small size particle aggregation might be easier happened at high gas velocities to form larger size bioaerosols.

### *Effects of Gas Temperature on Bioaerosol Emissions*

#### *Effects of Gas Temperature on Bioaerosol Concentration and Composition*

Fig. 3(a) describes the correlation between bioaerosol emissions and temperature in the biofilter. In general, the concentrations of bacterial and fungal aerosol were increased first and then decreased with the rise of temperature. In a certain range of temperature (< 50°C), a positive relationship was found between bacterial aerosol emissions and temperature in the biofilter ($R^2$ = 0.9906). When the temperature was about 50°C, the bacterial aerosol concentration in the outlet reached the maximum value of 223 CFU $m^{-3}$. This phenomenon might be due to the formation of large amounts of thermophilic bacteria in the biofilter. Thermophilic microorganisms had a unique adaptation mechanism, growing and multiplying at a high temperature environment. Their membrane lipid contained highly saturated fatty acids and could form a high strength hydrophobic bond, making the cell membrane maintained the stability and functionality at high temperatures. On the other hand, fungal aerosol concentration decreased as the temperature beyond 30°C. Some studies reported that the

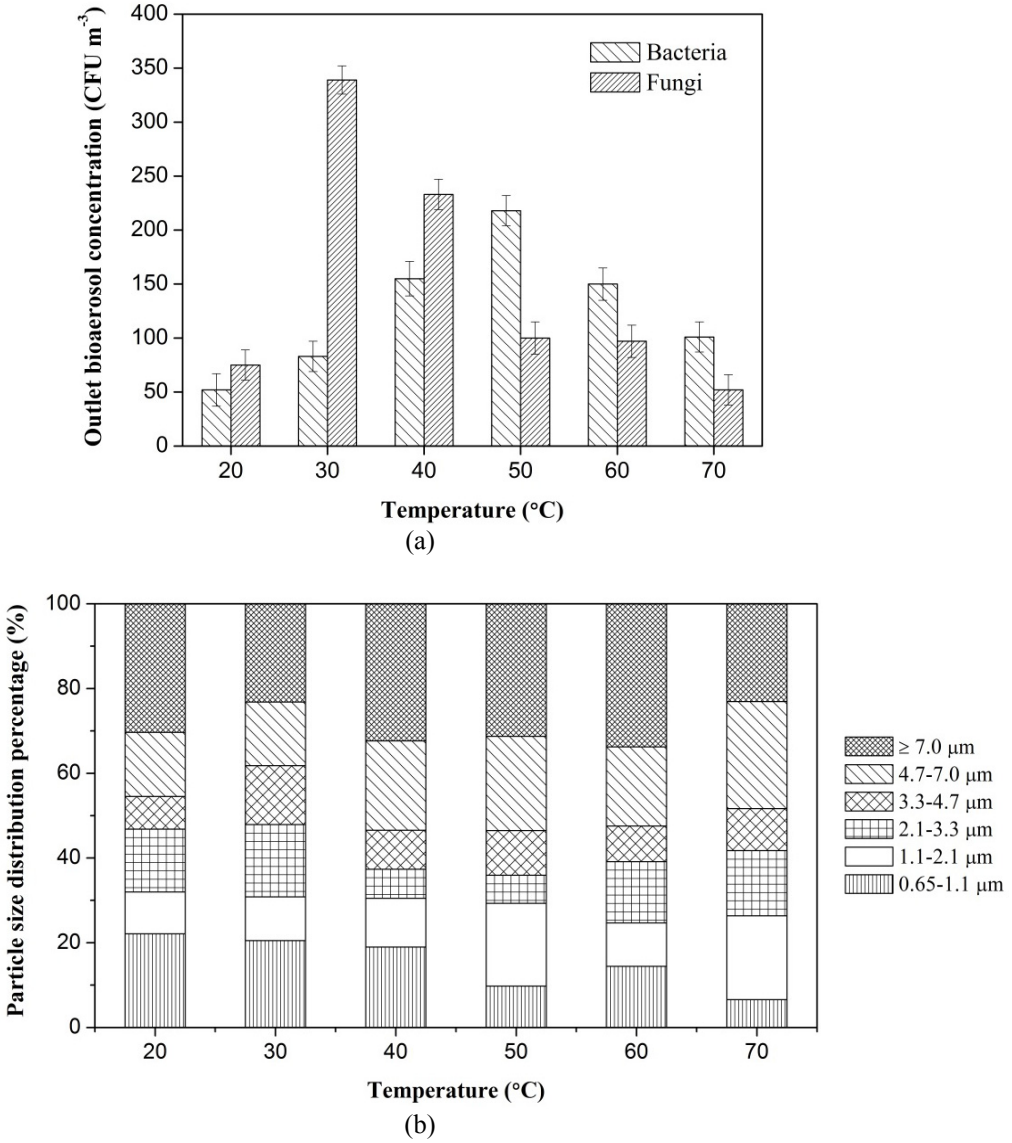


**Fig. 3.** The effect of different temperatures on bioaerosol emissions characteristic: (a) Concentration characteristic (b) Particle size distribution characteristic.

optimal temperature for fungi growth is around 25°C (Li *et al.*, 2015), thus it was suitable for fungi growth when operating temperature maintained at 30°C in biofilters. Rapid propagation of fungi occurred in this condition and a lot of microorganisms were brought out by exhaust gas, causing the increase concentration of fungal aerosol.

Furthermore, the heat exchange rate between the environment and microbial surface was controlled by temperature, affecting the viability of the microorganisms through intracellular water evaporation. Regarding the effects of temperature on viability of microorganisms, a high temperature can lead to protein denaturation, which will affect the survival of microorganisms, while a low temperature reduces microbial enzyme activity and can cause cells to go dormant, leading to cease of metabolization and death. Saari *et al.* (2015) also confirmed that different fluorescent bioaerosol particles mode were observed in summer and winter since the low biological activity in the wintertime. In addition, Fig. S3 shows that the outlet bacteria and fungi concentrations are larger than that of inlet, which indicates that the biofilter could be regarded as a bioaerosol emissions source.

*Effects of Gas Temperature on Particle Size Distribution*

The particle size distribution of the total bioaerosol emissions at different temperatures is shown in Fig. 3(b). In general, large particles (> 4.7 μm) accounted for approximately 50% of the total bioaerosol emissions and the value showed a minor fluctuation during the experiments. However, the proportions of the fifth (1.1–2.1 μm) and the sixth (0.65–1.1 μm) stage showed a large variation. The reason for this phenomenon is not clear, but it could be related to the different suitable microbial growth temperature with various particle sizes. For instance, the fine particles might be more susceptible to the effects of temperature.

### *Effects of Packing Bed Moisture Content on Bioaerosol Emissions*

*Effects of Packing Bed Moisture Content on Bioaerosol Concentration and Composition*

The concentration of bioaerosol emissions under different packing bed moisture content is illustrated in Fig. 4(a). With the increasing moisture content, the positive relationship between bacterial aerosol and moisture content could be anticipated ($R^2$ = 0.6496), as it has been previously reported (Giorgio *et al.*, 1996; Reinthaler *et al.*, 1997). The peak concentration of bacteria was 349 CFU $m^{-3}$ with a moisture content of 70%. Conversely, a negative relationship between fungal aerosol concentration and moisture content could be established ($R^2$ = 0.4126). Similarly, Nikaeen *et al.* (2009) also founded that the concentrations of total bacteria in compost-application samples decreased significantly with increasing moisture content. The highest concentrations of fungi (nearly 267 CFU $m^{-3}$) from the outlet of the biofilter were observed when the moisture content was about 40%. Such differences between fungal and bacterial bioaerosol emissions might be explained by the fact that fungi are more suitable for growing in a dry environment, while moist environments facilitate the growth of bacteria.

In addition, it was observed that when the moisture content reached to 90%, the concentration of total bioaerosol decreased substantially. Leaching effect caused by the moisture attached to the surface of the biofilm in the biofilter was the main reason for the decrease. The growth rate of the water film thickness may be faster than that of the biofilm with the increasing moisture content. As a result, some microorganisms can move freely in the water film. Therefore, these microbes may be brought out from the reactor by the leachate, reducing the concentration of bioaerosol emissions as moisture content above 90%. Fig. S4 shows the difference of bioaerosol concentration between inlet and outlet under different moisture contents. The outlet bioaerosol concentration was higher than inlet, which was similar to the previously observed behavior of other variables.

*Effects of Packing Bed Moisture Content on Particle Size Distribution*

Fig. 4(b) shows the particle size distribution of bioaerosol emissions at different moisture contents. With the change of moisture content, the proportion of the third stage (3.3–4.7 μm) was maintained at about 20% of the total bioaerosol emissions and showed a minor fluctuation. According to the results, it could also be found that the proportion of fine particles (< 2.1 μm) was decreased from 32% to 2%, while the coarse particles (> 4.7 μm) gradually increased from 38% to 55%, as moisture content increased. High moisture content may lead to a large size of droplets in the biofilter. A large droplet is conducive to microbial adhesion and aggregation, which increases the particle size, as founded in previous studies (Madelin *et al.*, 1992; Dong *et al.*, 2016). Such mechanism explains why the proportion of fine particles was reduced whereas the proportion of coarse particles was increased with the gradual increase of moisture content.

### *Effects of Different Factors on Suspended Particles Emission*

Fig. 5 demonstrates the effects of different factors on the suspended particles emission from gaseous biofilters, including (a) gas velocity, (b) temperature and (c) moisture content. In general, the concentrations of fine particles (< 1.0 μm) were between $1.0 \times 10^4$ and $6.7 \times 10^5$ particles $m^{-3}$ and the concentrations of coarse particles (1.0–10.0 μm) were between $1.0 \times 10^1$ and $9.9 \times 10^3$ particles $m^{-3}$. Furthermore, the concentration of fine particles was much higher than that of coarse particles, making the total particles concentration depend highly on the concentration of the fine particles.

Fig. 5(a) also shows the concentration and size distribution of suspended particles emission under different gas velocities. With the increase of gas velocity, the concentration of fine particles was increased from 62,761 to 273,331 particles $m^{-3}$, whereas the coarse particles concentration varied slightly, from 3,962 to 11,083 particles $m^{-3}$. The percentages of increased concentration of fine particles and coarse particles reached to 335.51% and 179.73%, respectively. These results indicated that fine particles were more susceptible to gas velocity and a highly positive

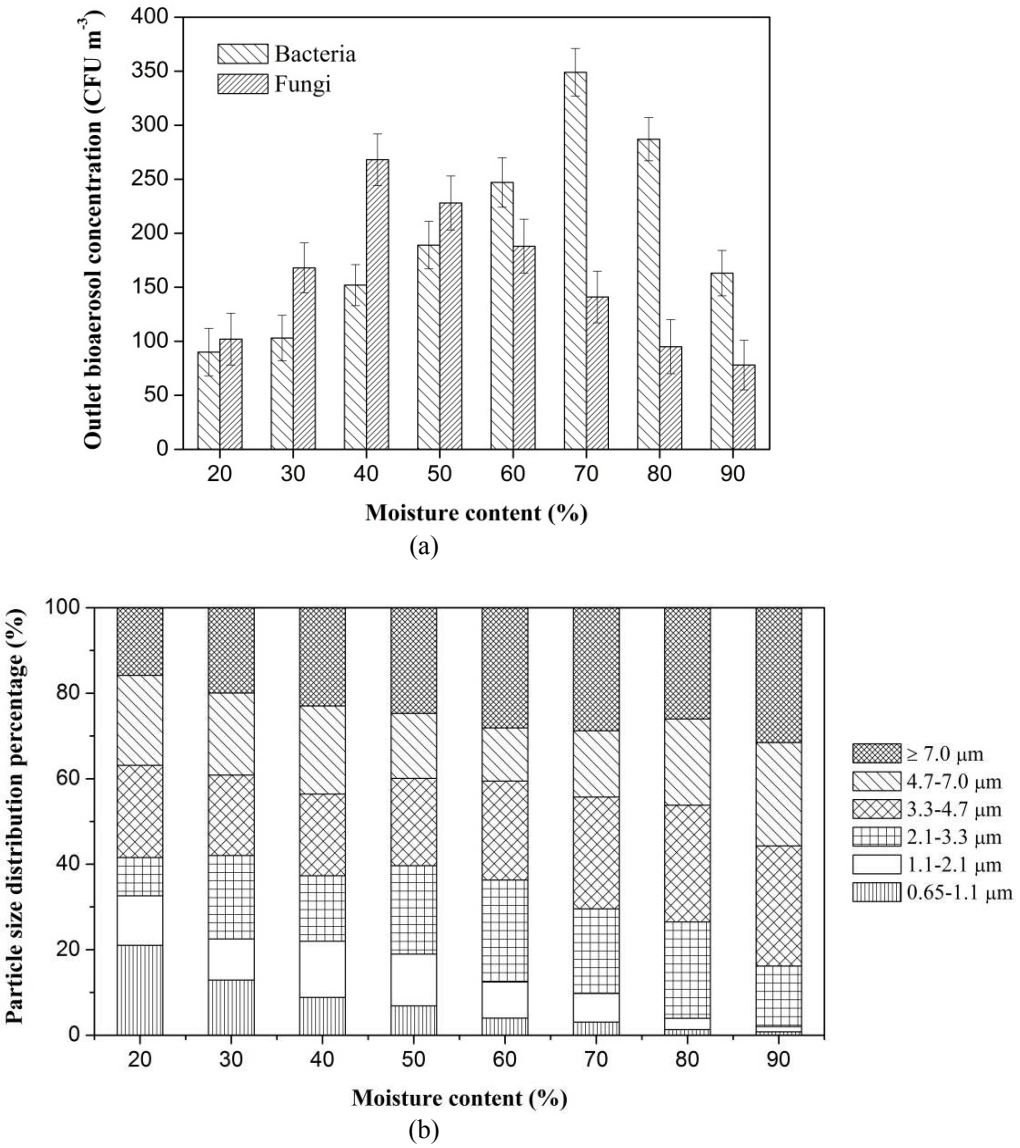


**Fig. 4.** The effect of different moisture contents on bioaerosol emissions characteristic: (a) Concentration characteristic (b) Particle size distribution characteristic.

correlation was presented between its concentration and gas velocity. This could be explained that fine particles were subjected to a small gravity and therefore, they were easier to be brought out from the biofilter.

The concentration and size distribution of suspended particles under different temperature are shown in Fig. 5(b). As the temperature rose, the concentration of fine particles (< 1.0 μm) was reduced, while the concentration of coarse particles (1.0–10.0 μm) showed the peak concentration at around 50°C or so. Fine particles and coarse particles concentrations ranged from 168,371 to 30,278 particles $m^{-3}$ and from 6,161 to 5,348 particles $m^{-3}$, respectively, within the studied temperature range. Particle concentrations with different aerodynamic diameters presented a decreasing trend at higher temperatures, which was also observed in Haas *et al.* (2013) studies.

Fig. 5(c) also shows the concentration and size distribution of suspended particles emission under different moisture contents. In this study, fine particles (< 1.0 μm) concentration increased from 89,638 to 253,517 particles $m^{-3}$, showing positive correlation with moisture content. On the other hand, coarse particles (1.0–10.0 μm) concentration was first increased and then decreased when the moisture content continued to rise, which was similar to that of suspended particles concentration in relation to temperature. Suspended particles contain water-soluble inorganic ions that can be adsorbed as condensation nuclei. Within a certain range, a high moisture content was more conducive to form large particulate matter. In addition, water-soluble inorganic salts are a major component of fine particles and thus, small size particles are easier to be affected by moisture content. The fine particles absorbed large amounts of water and was converted to the larger diameter particles. However, when the moisture content was too high in the biofilter, the larger particles gravitational settle, decreasing its concentration in the outlet.

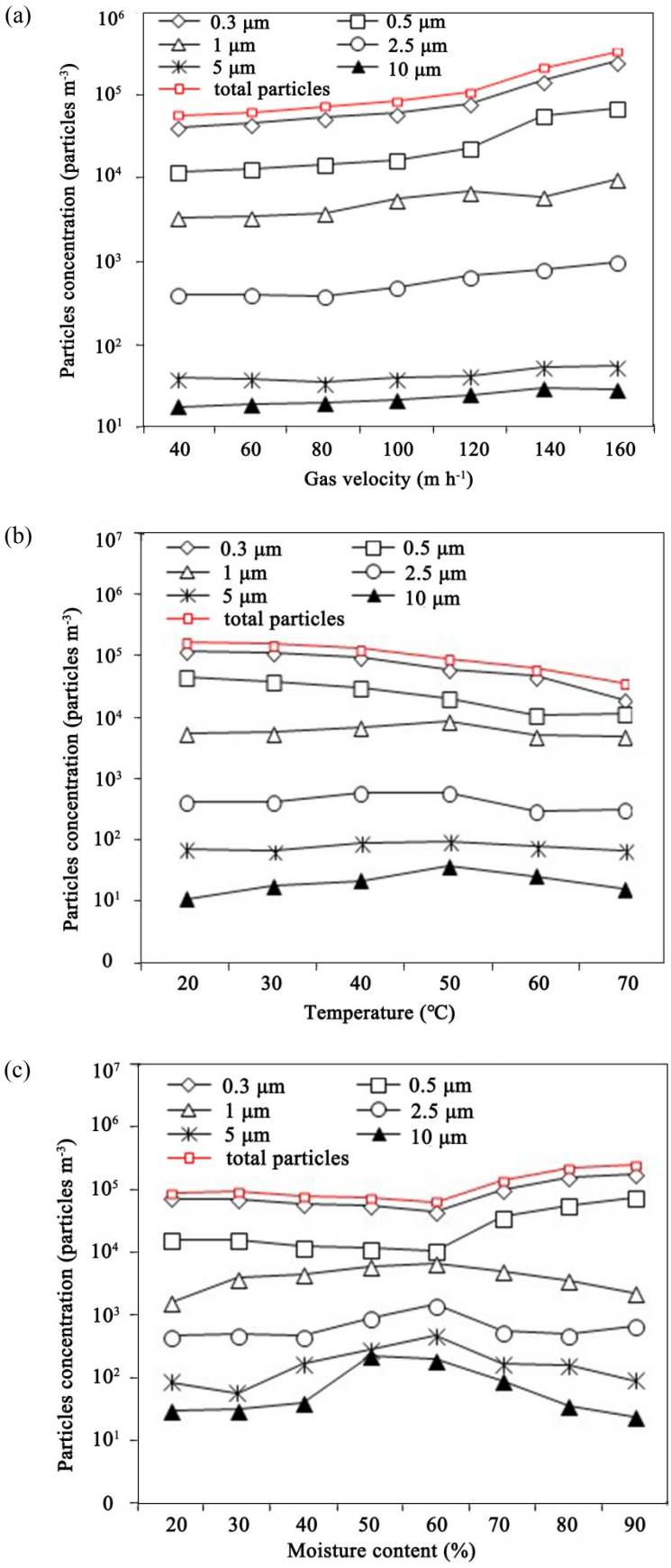


**Fig. 5.** The effects of different (a) velocities, (b) temperatures, and (c) moisture contents on the suspended particles emission.

***Relationship between Bioaerosol and Suspended Particles Emission***

The differences between inlet and outlet concentrations, including the bioaerosol and suspended particles, are shown in Fig. 6. The concentration of bioaerosol emissions from the outlet was larger than that at the inlet. Conversely, the concentration of suspended particles emissions from the outlet was lower than that at the inlet. These results indicated that biofilters have the capacity to filtrate particulate matter although it is regarded as a bioaerosol emissions source. The reason for this phenomenon might be related to their different characteristics between bioaerosol and suspended particles, including their particle size and source. In this study, the bioaerosol mainly comes from the biofilm in the biofilter. When the bioaerosol gets through the packing layer, some microorganisms, attached to the biofilm of the packing layer, are also brought out by the gas flow, causing the increasing concentration of bioaerosol emissions. On the other hand, the suspended particles derive from inlet air and have a larger particle size (~10 μm) than the bioaerosol. When such large particles go through the packing layer, they are easily blocked by the packing layer, thus reducing the concentration of suspended particles emitted from gaseous biofilters.

***Health Risk Assessment of Emitted Bioaerosol***

The results of bioaerosol exposure dose ($ADD_{inhalation}$ and $ADD_{skin}$) and total health risk (*HI*) to children, adult males and adult females were listed in Table 4. The variations of exposure dose to different groups were the same as the results of bioaerosol emissions concentrations. However, exposure doses via two pathways (inhalation and skin contact) were different in different sensitive population groups under same bioaerosol emission concentration. Inhalation dose of bioaerosol is much larger than skin contact. Generally, the orders of inhalation exposure dose presented as adult males > adult females > children. This might be explained by different inhalation rates among males, females and children. Similarly, highest *HI* value was also obtained in adult males group. Nadal *et al.* (2009) reported that workers exposed to biological agents, such as bacteria and/or endotoxins produced by them, showed a potential threat for infections. These results indicated adult males were under the highest risk of infections by bioaerosol emissions from a biofilters through inhalation.

## CONCLUSIONS

In this study, the concentrations of bioaerosols and suspended particles emission from gaseous biofilters were investigated at different velocities and temperatures and with different amounts of moisture. The results showed that the bioaerosol concentration in the biofilter was much higher than the background concentration of 60 CFU $m^{-3}$ (the bioaerosol concentration in the surrounding environment). A high gas velocity enabled easy transport of microbes from the carriers. When the temperature was 50°C, the bacterial aerosol outlet concentration reached its maximum value of 223 CFU $m^{-3}$, although the fungal aerosol concentration decreased at temperatures above 25°C. The peak bacterial concentration was 349 CFU $m^{-3}$, with a moisture content of 70%, whereas the highest fungal concentration was nearly 267 CFU $m^{-3}$, with a moisture content of 40%. In addition, the bioaerosol concentration changed under different experimental conditions.

The concentration of fine particles was much higher than that of coarse particles, and the total particle concentration mainly depended on the concentration of the former. High gas velocities, low temperatures, and high moisture content favored fine particle emissions. By contrast, changes in the concentration and size distribution of coarse particles under various operating conditions were not obvious. Moreover, a correlation between the behavior of the bioaerosols and of the total suspended particles in the biofilter was observed: The biofilter is a source of bioaerosol emissions and has a filtration function for suspended particulate matter.

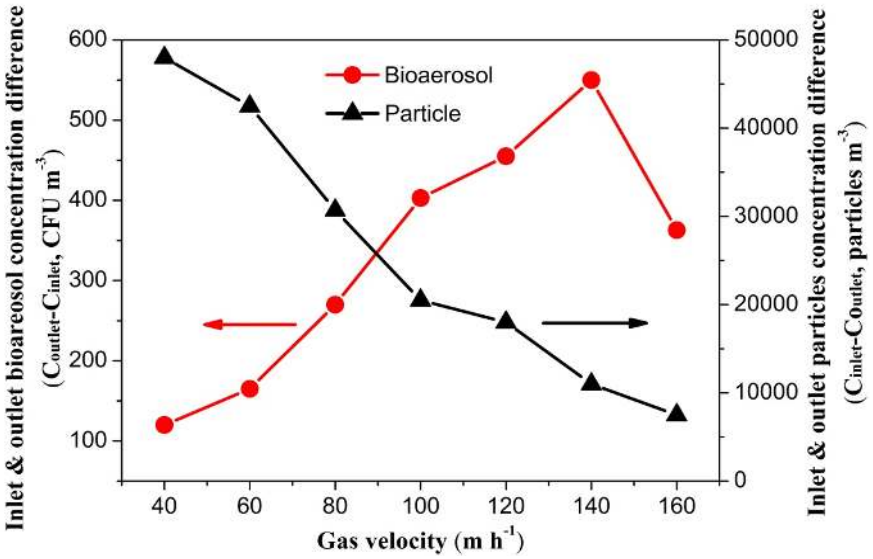


**Fig. 6.** The bioaerosol and suspended particles concentration differences between inlet and outlet.

**Table 4.** Evaluation of bioaerosol exposure dose and total health risk.

| Parameters | | $ADD_{inhalation}$ | | | $ADD_{skin}$ ($10^{-5}$) | | | $HI$ ($10^{-4}$) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Children | Adult males | Adult females | Children | Adult males | Adult females | Children | Adult males | Adult females |
| Gas velocity ($m\ h^{-1}$) | 40 | 4.19 | 10.38 | 8.38 | 6.39 | 11.58 | 12.77 | 8.38 | 20.76 | 16.76 |
| | 60 | 6.867 | 17.004 | 13.734 | 10.464 | 18.966 | 20.928 | 13.734 | 34.008 | 27.468 |
| | 80 | 8.65 | 21.42 | 17.30 | 13.18 | 23.89 | 26.36 | 17.3 | 42.84 | 34.601 |
| | 100 | 11.109 | 27.508 | 22.218 | 16.928 | 30.682 | 33.856 | 22.218 | 55.017 | 44.437 |
| | 120 | 13.23 | 32.76 | 26.46 | 20.16 | 36.54 | 40.32 | 26.46 | 65.521 | 52.921 |
| | 140 | 14.721 | 36.452 | 29.442 | 22.432 | 40.658 | 44.864 | 29.442 | 72.905 | 58.885 |
| | 160 | 12.138 | 30.056 | 24.276 | 18.496 | 33.524 | 36.992 | 24.276 | 60.113 | 48.553 |
| Gas temperature (°C) | 20 | 2.772 | 6.864 | 5.544 | 4.224 | 7.656 | 8.448 | 5.544 | 13.728 | 11.088 |
| | 30 | 4.032 | 9.984 | 8.064 | 6.144 | 11.136 | 12.288 | 8.064 | 19.968 | 16.128 |
| | 40 | 6.3 | 15.6 | 12.6 | 9.6 | 17.4 | 19.2 | 12.6 | 31.2 | 25.2 |
| | 50 | 6.867 | 17.004 | 13.734 | 10.464 | 18.966 | 20.928 | 13.734 | 34.008 | 27.468 |
| | 60 | 5.271 | 13.052 | 10.542 | 8.032 | 14.558 | 16.064 | 10.542 | 26.104 | 21.084 |
| | 70 | 3.255 | 8.06 | 6.51 | 4.96 | 8.99 | 9.92 | 6.51 | 16.12 | 13.02 |
| Moisture content (%) | 20 | 4.011 | 9.932 | 8.022 | 6.112 | 11.078 | 12.224 | 8.022 | 19.864 | 16.044 |
| | 30 | 5.481 | 13.572 | 10.962 | 8.352 | 15.138 | 16.704 | 10.962 | 27.144 | 21.924 |
| | 40 | 6.321 | 15.652 | 12.642 | 9.632 | 17.458 | 19.264 | 12.642 | 31.304 | 25.284 |
| | 50 | 6.867 | 17.004 | 13.734 | 10.464 | 18.966 | 20.928 | 13.734 | 34.008 | 27.468 |
| | 60 | 8.925 | 22.1 | 17.85 | 13.6 | 24.65 | 27.2 | 17.85 | 44.2 | 35.701 |
| | 70 | 10.311 | 25.532 | 20.622 | 15.712 | 28.478 | 31.424 | 20.622 | 51.065 | 41.245 |
| | 80 | 7.959 | 19.708 | 15.918 | 12.128 | 21.982 | 24.256 | 15.918 | 39.416 | 31.836 |

Bioaerosol emissions were evaluated with a mathematical model, which simulated the exposure dose and assessed the health risk. The health risk evaluation indicated that bioaerosol emissions from biofilters posed the highest risk of infection via inhalation to adult males.

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## SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at http://www.aaqr.org.

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