

Review

# A Review on Airborne Microbes: The Characteristics of Sources, Pathogenicity and Geography

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**Abstract:** Microbes are widespread and have been much more studied in recent years. In this review, we describe detailed information on airborne microbes that commonly originate from soil and water through liquid–air and soil–air interface. The common bacteria and fungi in the atmosphere are the phyla of *Firmicutes*, *Proteobacteria*, *Bacteroides*, *Actinobacteria*, *Cyanobacteria* and *Ascomycota*, *Basidiomycota*, *Chytridiomycota*, *Rozellomycota* that include most pathogens leading to several health problems. In addition, the stability of microbial community structure in bioaerosols could be affected by many factors and some special weather conditions like dust events even can transport foreign pathogens to other regions, affecting human health. Such environments are common for a particular place and affect the nature and interaction of airborne microbes with them. For instance, meteorological factors, haze and foggy days greatly influence the concentration and abundance of airborne microbes. However, as microorganisms in the atmosphere are attached on particulate matters (PM), the high concentration of chemical pollutants in PM tends to restrain the growth of microbes, especially gathering atmospheric pollutants in heavy haze days. Moreover, moderate haze concentration and/or common chemical components could provide suitable microenvironments and nutrition for airborne microorganism survival. In summary, the study reviews much information and characteristics of airborne microbes for further study.

**Keywords:** airborne microbes; pathogens; transportation; atmospheric components; geographical characteristics

## 1. Introduction

Microorganisms (including bacteria, fungi and viruses) associated with atmospheric particulate matters, are known as bioaerosols. It has been reported that bioaerosols contribute up to 25% to atmospheric aerosols [1]. Furthermore, it is known that as an important contributor, chemical pollutants in the atmosphere may cause adverse human diseases with gathering in airborne particulate matters, especially respiratory illnesses. In addition to chemical pollutants, airborne microorganisms loaded in atmospheric particles have received growing attention in recent years due to the evidence supporting their role in the atmospheric environment and potential implications for human health, agricultural productivity and ecosystem stability [2–6]. Today, many pathogens are included in the microbial community in bioaerosols and may cause severe health problems, such as asthma, respiratory infections, skin and wound infections, acne and allergic reactions [7–9].

Besides, the sources of airborne microbes are mainly dominant by marine, soil and then followed by microbe dispersal in some processing plants depended on role of microorganism. For instance,

many studies have proved that airborne microbes had the same characteristics and structure with marine and soil [10]. Droplet diffusion in composting plants, waste treatment plants and sewage treatment work—Which mainly rely on bacteria and fungi to degradation and disposal—Also contributes to increase the levels of microorganisms to the atmosphere [11,12]. The species of bacteria and fungi in bioaerosols are abundant and multiple. The common microbial phyla including *Firmicutes*, *Proteobacteria*, *Bacteroides*, *Actinobacteria*, *Cyanobacteria*, *Ascomycota*, *Basidiomycota* and *Chytridiomycota*, which have been proven to contain numerous pathogens. However, the stability of microbial community structure could hardly to maintain for a long time, as microbial living conditions in the atmosphere is inconstant (for example, relative humidity, temperature, light, chemicals, nutrition, etc.) under different meteorological parameters. Furthermore, the community structure tends to differ with the variation of survival conditions in different locations and regions they grow [13–15]. Therefore, as airborne microbes are mainly loaded in particulate matters in the atmosphere, the increased concentration of particulate matters in special weather conditions (dust event and haze days) will lead to greatly high levels of microbes [16–18]. However, due to the enriched atmospheric pollutants (PAHs, heavy metals, etc.) in particulate matters, the number of airborne microbes in heavy hazy days tends to decrease.

In this review, we describe the characteristics and transport behaviors of airborne microorganisms and the behaviors of pathogens in the atmosphere.

## 2. The Sources and Characterization of Airborne Microbes

The spread of microorganisms from liquid systems or soil (e.g., *Bacillus bataviensis*, *Sphingomonas*, *Arcobacter*) to the atmosphere is attributed to the dispersal of air current and droplets, which is the best explanation to the presence of some specific microorganisms presented in totally different environments (Table 1) [16,19–26]. In some studies, the only microorganism identified in the Antarctica soil was *Brevundimonas* sp., while *Sphingomonas* was in the Antarctic dust [24,27]. The microbial sources and communities structure in the eolian dusts of Southern Australia were studied [28], and the result showed that the microorganisms in saline lake sediments and biological soil crusts are the origin [29]. A highly diverse and abundant bacterial community was presented, due to the spread of air masses in an intense Saharan dust event [16]. Composting is a process based on the degradation of wastes by microbial activity. Many different bacteria and fungi are released during compost processing (fresh waste delivery, shredding, compost-pile turning and compost screening) [23,25]. The bacterial community structure studied in a wastewater treatment plant showed that the composition of microorganisms in water was one of the most important sources of bacterial community in bioaerosols [30]. Furthermore, plants and soil were also found to major sources of the airborne bacteria in aerosols [26]. Marine systems are the best survival environments for microorganism and includes millions of species of bacteria, fungi and minor protozoans [31]. In fact, aerosols and droplets created from the surface of aquatic systems are known to enrich and convey microbes through the liquid–air interface [21,32]. There are studies demonstrating that most microorganisms belonging to marine systems have been found in non-liquid environments [21,33]. In addition, the variability of airborne bacteria observed in urban Mediterranean area (Thessaloniki, Greece) showed that some species possibly originated from marine origin (e.g., *Synechococcus* sp.), while most species were from soil and wastewater origin [34].

**Table 1.** Source of representative species in aerosols.

Representative Species	Sources	Destination	References
<i>Sphingomonas</i>	Antarctic dust	Airborne microbes	[27]
<i>Helicobacter</i>	Wastewater treatment plants	Aerosolization	[22]
<i>Brevundimonas</i> sp.	Antarctica soil	Antarctic aerosol	[24]
<i>Stenotrophomonas</i> , <i>Acidovorax</i>	Saharan dust	Aerosol	[16]
<i>Thermoactinomyces</i> spp., <i>Aspergillus</i> spp.	Composting process	Aerosol	[23] [25]
<i>Sphingomonadales</i>	Common inhabitant of leaves	Megalopolis aerosol	[26]
<i>Burkholderiales</i> , <i>Pseudomonadales</i>	Soil inhabiting bacteria		

In fact, the conditions in the atmosphere are unfavorable for microorganisms, due to lack for nutrition and moderate survival microenvironment. For instance, microbial cells need to tolerate strong solar radiation, oxidants and loaded by particulate matters in the air that contain some potentially toxic molecules (e.g., formaldehyde), strong acids and some strong oxidants (e.g., hydrogen peroxide, radicals), which are potentially affecting the growth of microbial organisms [35]. However, despite these severe conditions, a considerable fraction of airborne microbes remains alive and maintains their activity. There are numerous species of airborne microbes tested in various reports, not only including pathogens also with common bacteria and fungi in bioaerosols. In the common bioaerosols of urban and subway area, the microbial community is mainly consisted by the phyla *Firmicutes* (*Thermoactinomyces*, *Bacillus*, *Staphylococcus*, *Streptococcus*, *Abiotrophia*), *Alpha*–, *Beta*– and *Gamma*–*Proteobacteria* (*Acinetobacter*, *Stenotrophomonas*, *Pseudomonas*, *Sphingomonas*, *Massilia*, *Delftia*, *Brevundimonas*), *Bacteroides* (*Empedobacter*, *Pontibacter*, *Adhaeribacter*, *Hymenobacter*), *Actinobacteria* (*Thermobifida*, *Streptomyces*, *Kitasatospora*, *Propionibacterium*, *Friedmanniella*) and *Cyanobacteria* (*Crinalium*) [34,36–42]. Compared to bacteria, the fungi species also were found in bioaerosol samples, including the genera of *Aspergillus* (*A. fumigatus*, *A. niger*, *A. ochraceus*, *A. sydowii*), *Penicillium*, *Alternaria*, *Emericella*, *Epicoccum*, *Fusarium*, *Cladosporium*, *Rhizopus* and *Mucor*, *Thermomyces*, etc. [25,39,43–46]. In special haze weather, the increased microbial species include microorganisms from the genera of *Methylobacillus*, *Tumebacillus*, *Desulfurispora*, *Okdonella*, *Caenimonas*, *Geminicoccus*, *Sphingopyxis*, *Cellulomonas* and *Rhizobacter* [47], due to the increased levels of particulate matters. Furthermore, the microbial community structure during Asian dust events clearly was distinguished from that on non-Asian dust days [48,49], as the additional transported foreign microorganisms caused by strong wind. For example, the genera *Bacillus* and *Modestobacter* were increased about 3–fold, while *Escherichia*–*Shigella* was decreased significantly during dust events [50].

### 3. The Effect of Atmospheric Particulate Matters (PM) on Airborne Microbes

As is known that the particulate matters (PM) are distinguished into two sorts according to particular diameter, fine particulates PM<sub>2.5</sub> (diameter <2.5  $\mu\text{m}$ ) and coarse particulates PM<sub>10</sub> (diameter between 2.5–10  $\mu\text{m}$ ) [17]. Generally, most airborne microorganisms are loaded by PM in the atmosphere, and numerous studies have studied the relationship between microbial quantity and particulates diameters [6]. In PM, the range of dynamic diameter can be distinguished into six stages,  $\geq 7.0 \mu\text{m}$  (Stage 1), 7.0–4.7  $\mu\text{m}$  (Stage 2), 4.7–3.3  $\mu\text{m}$  (Stage 3), 3.3–2.1  $\mu\text{m}$  (Stage 4), 2.1–1.1  $\mu\text{m}$  (Stage 5) and 1.1–0.65  $\mu\text{m}$  (Stage 6). The greatest proportion of airborne bacteria were detected on Stage 3 (3.3–4.7  $\mu\text{m}$ ) [51], which had the similar results with other studies [52,53]. It was further proved in other works that the size distribution of microbes presented an increase in fine PM on hazy days and an increase in coarse PM on foggy days, while presented one peak at 1.1–2.1  $\mu\text{m}$  and another peak at 4.7–7.0  $\mu\text{m}$  on sunny days [54]. The size distribution of airborne microbes was studied under severe haze periods, which showed various bacterial concentration in PM<sub>0.32–0.56</sub> (7314 cells/m<sup>3</sup>), PM<sub>0.18–0.32</sub> (7212 cells/m<sup>3</sup>) and PM<sub>0.56–1</sub> (6982 cells/m<sup>3</sup>) [6]. However, the fungi have variety of highest proportion in various stages under different regions and weather conditions (like sunny, cloudy or rain, etc.) [45,55]. The highest number of fungi with aerodynamic diameter ranging from 2.1 to 3.3  $\mu\text{m}$  were associated with coastal areas of bioaerosols [56]. It was revealed that the phenomenon that the quantities distribution of common fungi in PM<sub>10</sub> and PM<sub>2.5</sub> are diverse in an urban area, as different size fractions and chemicals (pollutants, O<sub>3</sub>, SO<sub>2</sub> and NO<sub>2</sub>) in two types of particulate matters [43]. Therefore, the concentration of microorganisms in different PM diameters has significant effects on the study of microbial community in bioaerosols, due to the application of sampling devices when collecting bioaerosol samples [57].

Furthermore, some chemical components in PM provide a media for airborne microorganism attachment—as well as a suitable microenvironment for their growth and survival in the air (Table 2). Recently, many studies are focused on the relationship between chemicals of PM and airborne microbes. One of studies reported that the bacterial community structure was most positively related to

water-soluble ions and metal elements ( $\text{SO}_4^{2-}$ ,  $\text{NO}_3^-$ ,  $\text{NH}_4^+$ ,  $\text{K}^+$  and  $\text{Cl}^-$ ), which indicated that these aerosol particles were of great significance on the bacterial compositions [58]. However, the effects of air pollutants on the atmospheric microbial community in heavy haze contaminated areas were found to decrease the abundance and richness of airborne microbes by restraining the growth of bacteria [46]. Besides, chemical components/pollutants in atmospheric PM were key factors that significantly altered the bacterial concentrations and community compositions [17]. The number of total airborne microbes appeared to increase firstly with the increased concentration of PM accumulation in the air, while began to decrease in severely polluted condition with greatly higher haze concentration [59]. Therefore, it is noteworthy that the competition between toxic effect and growth promotion components may contribute to this result, due to chemical pollutants adhering to PM. As discussion above, moderate concentration of particulate matters (PM) in the air bring about an increased concentration of microorganisms, such as in low-hazy, low-foggy and/or low-smog condition, in which some chemicals did not increase to sufficient quantities to cause noxious effects. However, in heavy air pollution and with considerably higher PM quantities gathering, the growth-promoting effect of the augmented levels of toxic and hazardous chemicals (sulfate, nitrate, polycyclic aromatic hydrocarbons (PAHs), etc.) greatly suppress the survival of microbes. Some studies have found that quantities of some heavy metals (like Pb, Zn, As) and PAHs in PM were about 3–8-fold higher during serious haze events than those on no haze days [60,61]. What is more, another study also revealed that the concentration of bioaerosol ascended once upon the haze occurrence and then decreased as the chemicals enriched in PM in the later periods of haze event [62]. It was found that the culturable bacteria and fungi had lower levels on severe haze days than on non-haze days [18].

**Table 2.** Factors that influence the characteristics of airborne community.

Factors		Ways
Particulate matters in hazy/foggy weather	Formaldehyde, $\text{O}_3$ , $\text{H}_2\text{O}_2$ , PAHs	Noxious effects on microbial growth
	Water-soluble ions, organic carbon	Provide habitat and nutrients for microbes
	Strong acids	Noxious effects
Strong solar radiation (UVs)		Noxious effects
Temperature (relative humidity)		Provide comfortable survival environment
Dust		Carry microbes to far distances
Thunderstorm		Uplift microorganisms in altitude above the tropopause

#### 4. The Effect of Airborne Microbes on the Environment

Numerous studies have focused on studying airborne microorganisms, as some of microbes in bioaerosols are considered as serious risk factor for health problems [63]. Table 3 lists the various types of airborne pathogenic microorganisms brought about health problems to human, plants and mammals. First, respiratory diseases caused by exposure to bioaerosols include aspergillosis in immunocompromised individuals, extrinsic allergic alveolitis, allergic rhinitis, asthma, upper airway irritation and mucous membrane irritation [64]. Brodie et al. revealed the consistent presence of pathogenic bacteria members in urban aerosol [20], in which bacteria from *Arcobacter*, *Helicobacter*, tick-borne *Rickettsia*, *Clostridium botulinum* type C, *Burkholderia mallei*, *Burkholderia pseudomallei* appear to be noxious for environment with leading to human health disease and mammals illness (for example, bacteremia, gastrointestinal, gastric ulcers, glanders and melioidosis) [12]. In their study, the samples were conducted from urban area of two U.S. cities, which indicated that many pathogenic microorganisms existed in urban area and had possibility to pose health threaten to city residents. Bioaerosol samples were studied from three main Chinese regions (Beijing, Tianjin and Hebei province) [26], where all experienced severe atmospheric pollution area usually. The study proved almost 18 pathogens species, among which, the dominant *Escherichia coli* could result in urinary tract infections, diarrhea, hemorrhagic colitis and hemolytic-uremic syndrome in humans [65].

The *Staphylococcus epidermidis*, a causative agent of implanted prostheses infections (e.g., heart valves and catheters), also dominated in the air. Besides, *Propionibacterium acnes* and *Enterococcus faecium* are known to cause acne and nosocomial infections, respectively [2,65,66]. The genera of *Pseudomonas* and *Acinetobacter* were tested in the urban area of Thessaloniki City [34] as well, which are known to cause respiratory infections and pneumonia, skin, wound infections, respectively [67,68]. In addition, *Staphylococcus* and *Ralstonia* [69,70] all accounted for mainly portions among the tested genera in bioaerosols, which are pathogen to human and plants, respectively [71]. There are several other pathogens detected in bioaerosols, as shown in Table 3 [72–76].

**Table 3.** Pathogens detected in different bioaerosols.

Phyla	Pathogen	Potential Pathogenicity	Host	Literature
Firmicutes	<i>Streptococcus gallolyticus</i>	pharyngitis, pink eye, meningitis, pneumonia, endocarditis, erysipelas, necrotizing fasciitis	Human	[26]
	<i>Streptococcus mitis</i>			
	<i>Staphylococcus</i>	food poisoning, herpetic and exfoliative dermatitis	Human	[69,71]
	<i>Bacillus circulans</i>	sepsis, bacteremia, abscesses, meningitis	Human	[41,42]
	<i>Enterococcus faecium</i> ;	nosocomial infections	Human	[65]
	<i>Staphylococcus epidermidis</i>	infections of implanted prosthesis (e.g., heart valves and catheters)	Human	[26]
Proteobacteria	<i>Arcobacter</i>	bacteremia, gastrointestinal illness	Human	[20]
	<i>Helicobacter</i>	gastric ulcers		
Gamma-proteobacteria	<i>Enterobacter cloacae</i>	potential infections of soft tissue, urinary tract and respiratory	Human	[26]
	<i>Pseudomonas aeruginosa</i>	nosocomial infections		
	<i>Aeromonas hydrophila</i>	release exotoxin to cause enteral infections		
	<i>Enterococcus casseliflavus</i>	respiratory infections		
	<i>Enterococcus haemolyticus</i>	urinary tract		
Gamma-proteobacteria	<i>Pseudomonas</i>	respiratory infections	Human	[34]
	<i>Acinetobacter</i>	pneumonia, skin and wound infections		
	<i>Acinetobacter baumannii</i>	pneumonia, bacteremia, meningitis		
Actinobacteria	<i>Propionibacterium acnes</i>	acne	Human	[2]
	<i>Thermoactinomyces vulgaris</i>	hypersensitivity-induced pneumonitis	Human	[9,25,72]
	<i>Saccharopolyspora rectivirgula</i>	alveolitis, bronchial asthma		
Proteobacteria	<i>Klebsiella pneumoniae</i>	mucormycosis, organic dust toxic syndrome (ODTS)	Human	[73][74]
Ascomycota	<i>Aspergillus fumigatus</i>			
Basidiomycota	<i>Bjerkandera adusta</i>	chronic cough	Human	[75]
Ascomycota	<i>Aspergillus fumigatus</i>	invasive aspergillosis	Human	[11,25]
Gamma-proteobacteria	<i>Escherichia coli</i>	diarrhea, sepsis	Infant, immature livestock	[26]
Firmicutes	<i>Clostridium botulinum</i> Types C	release exotoxin to cause disease	Mammals, fish, birds	[20]
Alpha-proteobacteria	Tick-borne <i>Rickettsia</i>	the medium of disease spread		
Beta-proteobacteria	<i>Burkholderia mallei</i>	glanders		
	<i>Burkholderia pseudomallei</i>	meliodosis	Mammals	
Firmicutes	<i>Bacillus</i> sp.	biodegradation	Mural paintings	[76]
Heterokontophyta	<i>Phytophthora infestans</i>	potato late blight	Plants	[3]
Ascomycota	<i>Cryphonectria parasitica</i>	chestnut blight		
Basidiomycota	<i>Puccinia melanocephala</i>	sugarcane rust		
Beta-proteobacteria	<i>Ralstonia</i>	a plant pathogen		

Some special plants and/or working environment all would release numerous numbers of bioaerosols within some pathogenic bacteria including Actinomycetes and fungi. For instance, bioaerosols released from composting plants have caused great concern due to their potential impacts on health of worker and public living closely to composting facilities. The biological hazards emission from composting activities usually include fungi, bacteria and endotoxin [77]. Le Goff et al. sampled at five French composting plants, in which the dominated fungi and bacteria were *Penicillium* sp., *Aspergillus fumigatus*, *Thermomyces lanuginosus*, etc. and *Bacillus* sp., *Geobacillus thermodenitrificans*, *Saccharopolyspora rectivirgula*, etc., respectively [25]. *Aspergillus fumigatus*, which is an opportunistic



fungal pathogen, may cause invasive aspergillosis in immuno-weak individuals under long-term exposure [11,44]. Besides, *Thermoactinomyces vulgaris* and *Saccharopolyspora rectivirgula* are associated with hypersensitivity induced pneumonitis and other allergies like alveolitis and/or bronchial asthma [9,72]. The airborne microorganisms may also be able to survive by long-distance transport in the atmosphere, thus some pathogens release from the composting process lead to greatest concern [78]. Besides, livestock farms are also known to emit large amounts of bioaerosols [79] and working or residing at closely areas with high gathering of livestock farms are easily to develop severe respiratory health problems [80–82]. The microbiome composition in bioaerosol originated from livestock farms was conducted, in which several potential pathogens were identified, such as *Streptococcus bovis*, *Serratia entomophila*, *Aerococcus viridans* and *Corynebacterium xerosis*, which are considered as infectious agents in human skin, lung, and/or the urinary tract infections for (feeble) individuals [36]. Furthermore, once people expose to high density of bioaerosols, they are more likely to develop organic dust toxic syndrome (ODTS), which includes a series of human illnesses, namely, mucormycosis, respiratory, urinary tract and gastroenteric tract infections and results from pathogens such as *Klebsiella pneumoniae*, *A. fumigatus*, *Rhizopus microspores*, *Erwinia Klebsiella*, *Enterococcus caselliflavus*, *Enterococcus haemoperoxidus* and *Acinetobacter baumannii*, respectively [74,83].

Pathogens of airborne microbes lead to diseases or allergic reactions and thus causes serious attention. Actually, people who expose to some special working environment, are more likely to develop illness discussed above. For example, people who work in mineral processing, agricultural and food processing, waste solid or water treatment factories have greatly possible to get diseases caused by pathogenic microorganisms. Besides, in special atmospheric conditions (dust event and haze days), the chance that human obtains health disease will increase to some extent. In addition to human beings, livestock, mammals and other matters in environment (plants, agricultural crops, statues, paintings, etc.) also will be ill caused by airborne microbes. *Bacillus decolorationis* sp. nov. was revealed to be responsible for the biodeterioration to mural paintings with causing discoloration on paintings [76]. Moreover, the plants also suffered from diseases, causing by microorganism in the atmosphere [3].

Besides, some studies have revealed that the microorganisms in bioaerosols could indirectly influence global climate and atmospheric processes [84–86]. For instance, airborne microorganisms contribute to participating in numerous atmospheric physicochemical processes: the formation of cloud droplet, precipitation, ice nucleation and the degradation of chemical compounds in cloud water [4,87,88]. Specific species of bacteria, fungi and plankton were reported to act as ice nuclei and are responsible for initiating the ice clouds formation [89,90] and found that ice nucleation activity of ice nuclei consisted by microorganisms is better than those of inorganic substances. Actually, bacteria and fungi that composed ice nucleation active proteins can increase the temperature of initiating ice formation at warmer than  $-5\text{ }^{\circ}\text{C}$  [91], while high temperature tends to decrease the activity of ice nuclei synthesized by inorganic matters. In addition, the ice nucleation activity of fungi and lichen could keep stable at temperatures up to  $60\text{ }^{\circ}\text{C}$  [92–94]. It was found that the ice nucleation active genera *Xanthomonas* even holds much of their ice nucleation activity at temperatures as many as  $105\text{ }^{\circ}\text{C}$  [5] and also revealed that the ice nucleation activity of pollen is not influenced by increasing temperature treatment at about  $100\text{ }^{\circ}\text{C}$  [95].

## 5. The Geographical Characteristics of Airborne Microbes

The earth's atmosphere is an extreme environment for microbial life, as it has low levels of nutrients, but strong UV radiation that could prevent microbial survival. However, the behavior and habit of microbial community in aerosols are rarely to predict and describe. There are various factors (relative humidity, temperature, season, special weather conditions: haze and dust, etc.) in the atmosphere, which have much possibility to influence microbial abundance. Thus, to study and figure out microbial composition and how it varies with different atmospheric factors, geographical characteristics has great significance.

The microbial concentration and community structure could hardly maintain stability in bioaerosol for a long time, due to the air masses and various meteorological conditions. It is known that the microbial concentration varies with different seasonal characteristics. The concentration of total microbes in the atmosphere appeared to the highest quantity in winter and the lowest in summer [54], as serious hazy and foggy weather emerging with higher particulate matters becoming inhabitants for microorganisms. There are various factors that influence microorganism activity in bioaerosols [96] and its results of principal component analysis (PCA) indicated that the season, haze levels, and sampling periods are mainly associated with influencing on bioaerosols. The lowest bacterial concentration of  $7.05 \times 10^2 \pm 4.74 \times 10^2$  CFU/m<sup>3</sup> were detected in summer season in by researchers [56,97], attributing to the high intensity of solar radiation [98], high ozone and high temperature (Tang, 2009). In addition to various seasons, meteorological factors also influence the microbial concentration. It was found that several atmospheric factors cause stress to the survival of microorganisms in bioaerosols with freeze–thaw appeared to be the greatly stronger factor, followed by oxidants and solar light, which had limited impacts on microorganism survival as well [99]. According to other studies, temperature had the strongest correlation with bacterial community composition [10,43,47,100]. However, relative humidity showed negative relationship with fungi [101], while there was no relationship of fungal concentration with solar radiation [102]. Nevertheless, the almost opposite conclusions and results in different reports may be because of various sampling locations and periods. Further, this trend of seasonal characteristics considerably is various under different locations or regions, as the levels of particulate matters and meteorological parameters are different. The concentration of microorganisms in bioaerosols are list in Table 4, which shows that the concentration in different locations and regions. The details on how various factors influence the diversity of microorganism and microbial composition in the atmosphere were provided in other study [39]. In their study, authors proved that geographic location, season and local climate influence the microbial communities, in which location accounted for large proportion on influencing the bacterial community composition. The highest bacterial abundance was recorded during summer in other study as well [34], but no significant seasonal differences were found between summer and winter in Thessaloniki, Greece. Additionally, higher quantities of microorganisms were revealed in autumn in Qingdao, China [56], while relatively high levels of airborne bacteria were found in both fall and spring seasons in northern Colorado, USA as well [103]. Another remarkable example on airborne fungal spore was reported from more northerly location in Stockholm where low winter temperatures significantly decreased spore concentrations and a snow cover caused a drop to even zero level [104]. Therefore, it is significantly important to enhance our comprehension of how various factors shape the abundance and composition of airborne microbes in different environments by studying spatial and temporal differences [15]. For example, the distribution of airborne microbes with elevation was studied in an Asian dust downwind area [105], in which concentrate microorganisms from continental and marine areas carried by the westerly winds. Moreover, the study shows that the bacterial community (e.g., *Bacillus*, *Actinobacterium* species) primarily consisted of terrestrial bacteria at the altitude of 3000 m. On contrast, at 1000 m and 10 m, those included marine bacteria (e.g., the classes *Cyanobacteria* and *Alphaproteobacteria*). Besides, another study conducted in a high elevation research station showed that bacterial abundances varied from season (the highest concentrations in fall and spring) and consistent with the changes in total particle concentrations as previously mentioned [103].

Compared with seasonal features, the characteristics and concentration of microorganism tend to show considerable variations during special weather conditions (like dust, haze, monsoon, thunderstorm, etc.). It had been demonstrated that microbial community structures could be altered by long–range and/or short–range transport [13,14], especially under dust events. The dust event could transport pathogenic microorganisms [106], such as allergen burden and asthma [75] and possibly lead to the dispersal of diseases such as Kawasaki disease in humans [107] and rust diseases in plants [3]. *Bacillus circulans* was found to transported during dust event, which is reported to cause sepsis, bacteremia, abscesses and meningitis in humans [50]. Besides, the bacterial abundance in

dusty and non-dusty weather condition indicated that the bacterial abundance on Asian dust days was considerably increased by approximately five-fold (from  $2 \pm 3 \times 10^3$  to  $1 \pm 0.6 \times 10^4$  cells/m<sup>3</sup>) [48]. In addition to dust weather, the haze and foggy weather conditions also exert great effects on microbial characteristics in bioaerosols [47,54]. What is more, thunderstorm have been studied to exert influences on airborne microbes. It was proved by the presence of microorganisms (e.g., *Deinococcus*, *Staphylococcus*, *Brevibacterium*), which were collected and isolated in stratosphere of atmosphere [108,109]. Numerous bacteria including Actinomycetes and fungi living in about 20–50 km elevation (e.g., *Actinobacteria*, *Bacillus* spp., *Actinomyces* sp., *Halorubrum lacusprofundi* etc.) were reviewed in other study [110]. Furthermore, the existence of microorganisms in high elevation ascribing to thunderstorm event was also reported [111], as microorganisms could carry high internal electric charges [112] and under thunderstorms, the strong electric fields could expedite charged microbes particulates rapidly up into high altitudes [113–117].

**Table 4.** Concentration of bacteria and fungi in different regions and weather conditions.

Concentration (cfu/m <sup>3</sup> )	Regions	Sites	Literature	
(bacteria) 565 ± 464 (fungi) 399 ± 371	Xi'an, China	nearby city major roads	[51]	
(bacteria) 81 ± 31 (fungi) 96 ± 45	Seoul, Korea	building (out)	[113]	
(bacteria) 125 ± 51 (fungi) 253 ± 121		forest		
(bacteria) 1110 ± 976 (fungi) 948 ± 978		building (out)		[53]
(bacteria) 45–591 (fungi) 4–28	Jeddah, Saudi Arabia	university campus	[43]	
(fungi) 800 1344	Brisbane, Australia	indoor school outdoor school	[114]	
(bacteria) (heavy hazy) 224 ± 186 (non-hazy) 358 ± 349	Beijing, China	roof of a building	[115]	
(fungi) 0–3882	Cincinnati Americ	homes area	[116]	
(bacteria) 0–2500	Graz, Austria	city center	[97]	
(bacteria)(downtown) 1700 ± 595 (bacteria) (River valley) 40,100±21,689	Tijuana, Mexico	/	[117]	
Concentration (cells/m <sup>3</sup> )	/	/		
(summer) 12 × 10 <sup>4</sup> (winter) 8.4 × 10 <sup>4</sup> (spring) 2.38 × 10 <sup>5</sup>	Thessaloniki, Greece	city center	[34]	
(summer) 1.66 × 10 <sup>5</sup> (autumn) 4.22 × 10 <sup>5</sup> (winter) 6.77 × 10 <sup>5</sup>		urban area		
(hazy) 7.09 × 10 <sup>5</sup> (foggy) 9.00 × 10 <sup>5</sup>				
(non-hazy) 6.55 × 10 <sup>5</sup> (dust) 1 ± 0.6 ×10 <sup>4</sup>	Qingdao, China	roof of a campus building	[54]	
(non-dust) 2 ± 3 ×10 <sup>3</sup>				
(hazy) 6.12 × 10 <sup>5</sup> ± 3.50 × 10 <sup>5</sup> (non-hazy) 2.15 × 10 <sup>5</sup> ± 1.26 ×10 <sup>5</sup>	Osaka, Japan	downtown area	[48]	
	Xi'an, China	urban area	[59]	

Thus, due to the transported microorganisms from external regions, the indigenous microbial community structure may be impacted by foreign microorganisms. For instance, microbial community tend to have a competition for resources (e.g., nutrients) [118]. It was revealed that microbes in aeolian dust may have a greater impact on indigenous microbial communities in the downwind areas near the dust source [119]. There could exist two causes accounting for the increase of airborne microbial concentration on hazy days. First, some atmospheric factors including temperature, relative humidity, and the concentration of atmospheric chemicals like as PM<sub>2.5</sub>, PM<sub>10</sub>, NO<sub>2</sub> and SO<sub>2</sub>, etc. were higher on hazy days than on non-hazy days. Secondly, the stable stratification and lower wind velocity on hazy days created an adverse environment for the dispersion of particulate matter, which provide



more comfortable environment for airborne microbes. However, although most studies showed that the haze days event could increase the microbial abundance, the study proved that higher PM<sub>2.5</sub> concentration may cause lower bacterial richness and diversity during heavy haze days [58], due to that there are numerous chemical pollutants and secondary pollutants in severe haze atmosphere, which could restrain the growth of airborne microbes. No matter how haze days could bring about more nutrition or chemical pollutants for airborne microbes to increase or decrease its concentration, the possible reason for such conditions is that the concentration and characteristics of airborne microbes are various with different locations and regions, as discussed above.

## 6. Conclusions

In conclusion, although the atmosphere is such an adversity environment for the growth of airborne microbes, the richness and abundance of microorganism is very high in the air. Moreover, almost all are loaded in particulate matters (PMs), thus the size distribution of PMs may influence the microbial community structure in various range of particles diameters. However, the microorganisms surviving in aerosols also may be affected by different factors (for example, meteorological parameters, the concentration of PMs, sampling locations and periods, etc.). Moreover, it has been demonstrated that the special weather conditions like dust events, haze and foggy days will affect microbial community structure and microbial concentration, especially on indigenous microbes. In fact, it is the truth of numerous pathogenic microorganisms have caused much attention, and most are able to transport by strong wind speed like under dust events. Therefore, these pathogens could lead to severe health problems to human, animals and even plants with greatly wide range in the air. In words, the more information of airborne microbes (especially pathogens) the more measures and studies we could conduct.

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