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# 沙尘天气对大气生物气溶胶中微生物浓度、特性和分布的影响*

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**摘 要**:生物气溶胶对全球气候、空气质量、大气过程和人体健康均具有重要影响。每年爆发的沙尘事件,使得生物气溶胶可借助沙尘进行长距离输运,从而影响到下风向地区生物气溶胶的浓度和性质。综述了沙尘天气下生物气溶胶中微生物的浓度、特性和分布特征的研究现状。已有研究显示,沙尘发生时,生物气溶胶中不同类别微生物的组成比例会有显著变化,细菌和真菌相对贡献随之改变。可培养细菌、真菌和总微生物浓度,均在沙尘天气下显著增加,但不同地区不同种类微生物在沙尘天气下的增加幅度相差很大。生物气溶胶中微生物主要分布于粗粒子中,其粒径分布受到沙尘天气的较大影响,而且不同种类微生物粒径分布的变化并不相同。沙尘发生时,生物气溶胶中的微生物群落结构与优势微生物也会发生明显改变。沙尘天气对生物气溶胶浓度、粒径分布、群落结构和活性的影响程度和影响机制,还需要进一步深入研究。

**关 键 词**:沙尘;生物气溶胶;微生物;粒径分布;群落结构
**中图分类号**:P425.5;X513 **文献标志码**:A **文章编号**:1001-8166(2018)06-0568-10

## 1 引 言

生物气溶胶是大气气溶胶的重要组成部分,可占到气溶胶粒子总浓度的 30%左右[1]。生物气溶胶通常来自于陆地和水生环境的生物活动[2],主要由含有微生物或生物大分子等生命活性物质的生物微粒组成,包括细菌、真菌、病毒、花粉、孢子和动植物碎裂分解体等具有生命活性的粒子[2,3]。生物气溶胶还可以改变大气中冰核(Ice Nuclei,IN)和云凝结核(Cloud Condensation Nuclei,CCN)的数量和特性[4~10],进而影响云量和气候变化,并会对人类社会发展造成影响[11]。生物气溶胶对空气质量和人体健康也具有明显的影响[12~16]。

天气条件对生物气溶胶中微生物的浓度、特性、分布等具有较大影响。在大风和强垂直对流等特定天气下,生物气溶胶可以借助沙尘暴事件进行长距离输运,并向大气输入大量的微生物,从而影响空气中微生物的分布和传输,并会扩大一些有机体的生物地理范围。每年亚洲和非洲沙尘暴事件产生的气溶胶多达几十亿吨[17]。2000—2012 年,我国北方共出现 157 次沙尘天气过程,平均每年发生 12 次沙尘天气过程[18]。沙尘粒子不仅载有大量的化学物质,还携带着生物气溶胶。以往对沙尘长距离输送的生物气溶胶的研究非常有限,因为人们通常认为沙尘

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中的微生物在长距离传输过程中会因太阳紫外线、营养匮乏及干燥失水而死亡。实际上,大部分真菌和一些种类的细菌都能形成孢子,可以耐受干燥、高温、辐射和营养匮乏等条件[19]。从气溶胶样品中分离出的许多细菌含有色素,能有效避免紫外线的损伤[20];此外,云、雾、烟和沙尘粒子对微生物也有一定防护作用[20~22]。已有的研究表明,沙尘在传输过程中会向下风向输送大量生物气溶胶,从而影响该区域生物气溶胶的浓度和特性[23~27]。此外,沙尘中的生物物质,如细菌和有机物质等,可能会增强冰云形成和降水的效率[28,29]。沙尘中的生物物质也可能导致疾病的增多,Liu 等[30]研究发现亚洲沙尘气溶胶中的某些微生物能够导致过敏性的肺部疾病,Ichinose 等[31]研究发现,亚洲沙尘中的微生物可能会引起与卵清蛋白相关的嗜酸性细胞肺部炎症的加重,大气中的霉菌、细菌等可能会直接影响人体健康。

鉴于沙尘天气对生物气溶胶浓度、性质和分布特征的重要影响,近年来许多相关研究工作已相继开展。本文综述了沙尘天气发生时,生物气溶胶的浓度、粒径分布、微生物群落及活性等相关方面的研究进展。

## 2　生物气溶胶的微生物组成特征及沙尘天气的影响

空气微生物是生物气溶胶中非常重要的一类,也是生物气溶胶的重要组成部分。从培养特征来说,微生物可以分为可在培养基上培养生长的“可培养”微生物和无法在培养基上培养生长的“不可培养”微生物。“可培养”微生物一般用平板计数法测定,根据所用培养基的不同,可以测定空气中的细菌、真菌和放线菌等。徐文兵等[32]提出了利用 DAPI 与 DNA 发生特异性结合,释放出蓝色至青绿色荧光,从而运用荧光显微镜计检测大气颗粒物中总体微生物(除完整孢子状真菌外)的方法,并成功测得青岛大气生物气溶胶中的总微生物为 $8.52\times10^4$ ~ $2.11\times10^6$ cells/$m^3$[32~35]。Sahu 等[36]研究发现环境中“可培养”微生物只是总体生物气溶胶中的一小部分,占比不到 1%。青岛的研究与此结果一致,生物气溶胶中主要是“不可培养”微生物,“可培养”微生物只占总微生物的 0.65%,但是所占比例随季节变化较大,为 0.25%~0.87%[32,34]。Li 等[34]发现,沙尘天气发生时,“可培养”微生物增加了 222.8%,“可培养”微生物占总体微生物的比值从沙尘发生前的 0.26%迅速增加到了 0.49%。可见,沙尘天气会对生物气溶胶中不同类别微生物的组成比例有显著影响。

在“可培养”微生物中,真菌和细菌对可培养菌的贡献随研究区域不同而有较大变化。沈阳、北京、南京、北海和西安等地区大气中可培养细菌浓度高于真菌,细菌与真菌浓度的比值为 1.1~4.1 倍,随研究区域变化很大[37~42]。Agarwal 等[43]也在新德里发现空气中可培养细菌的浓度高于可培养真菌。而 Karbowska-Berent 等[44]对波兰室内空气中的可培养细菌和真菌的测定结果显示,有些点位细菌显著高于真菌,而其他点位则相反。陈浩文[41]于 2001—2002 年用沉降法研究青岛空气中可培养细菌和真菌的浓度,发现细菌是“可培养”微生物的主要贡献者,是真菌浓度的 7.3 倍;而 2009—2010 年 Li 等[34]用分级采样器研究的结果显示青岛空气中可培养真菌的贡献略高于细菌,占“可培养”微生物的比例平均为 65%;韩晨等[45]发现,2015 年青岛空气中可培养真菌占有绝对优势,平均浓度是可培养细菌的 11 倍。可见,生物气溶胶中真菌和细菌对“可培养”微生物的贡献不仅随地域变化而且随时间也在发生变化。Li 等[34]发现沙尘天气下,青岛生物气溶胶中可培养细菌和真菌浓度分别增加了 174%和 50%,细菌对“可培养”微生物的贡献从非沙尘天的 59%增加到了 72%。在伊朗[46]、以色列[47]和加勒比海[48],同样观测到沙尘事件对可培养菌组成影响较大,“可培养”微生物中细菌的比例从非沙尘天的 42%~52%增加到了沙尘天的 53%~83%。这些研究结果表明,沙尘事件会改变生物气溶胶中可培养细菌和真菌的相对贡献。

## 3　沙尘天气对生物气溶胶中微生物浓度和粒径分布的影响

### 3.1　沙尘天气对生物气溶胶中微生物浓度的影响

长距离传输沙尘事件对下风向地区生物气溶胶浓度的影响已有一些研究。非洲沙尘通常从大西洋向西传播到美洲和加勒比海,从不列颠群岛向北到斯堪的纳维亚半岛,穿过地中海到欧洲,再进入亚洲西南部[17]。在非洲沙尘事件中观测到,生物气溶胶中的可培养细菌和真菌等微生物浓度会较非沙尘天气显著增加[24,26]。Kellogg 等[22]在西非马里地区的研究发现,沙尘期间可培养细菌和真菌的浓度明显增加,分别从背景期的 200~1 100 bacterial CFU/$m^3$ 和 0~130 fungal CFU/$m^3$ 增加到了 720~15 700 bac-

terial CFU/$m^3$ 和 80~370 fungal CFU/$m^3$。Soleimani 等[46]在中东沙尘事件中也发现了“可培养”微生物浓度的明显增加,室外可培养细菌和真菌浓度从非沙尘天的 423 CFU/$m^3$ 和 596 CFU/$m^3$ 增加到了 1 257 CFU/$m^3$ 和 1 116 CFU/$m^3$,室内可培养细菌和真菌浓度由非沙尘天的 329 CFU/$m^3$ 和 386 CFU/$m^3$ 增加到了 406 CFU/$m^3$ 和 550 CFU/$m^3$。Schlesinger 等[47]在以色列也观测到沙尘期间大气中“可培养”微生物浓度大幅上升。当沙尘传输到海洋上空时,带来了大量的外源微生物,也会导致海洋上空生物气溶胶中微生物浓度的增加。Griffin 等[48]观测到沙尘天气下加勒比海上空大气中可培养微生物浓度明显增加,是非沙尘天微生物浓度的 5.2 倍。此外,Griffin 等[49]于 2003 年观测到非洲沙尘向北美传输过程中,大西洋中脊地区大气中“可培养”微生物浓度与沙尘颗粒物浓度呈显著正相关。

亚洲沙尘通常从塔克拉玛干沙漠和戈壁沙漠向东传播,横跨韩国、日本和太平洋,并能够影响到北极、夏威夷群岛和美国西海岸地区[17]。亚洲沙尘期间,首尔地区生物气溶胶中的可培养细菌浓度明显增加,并且与总悬浮颗粒物(Total Suspended Particulate,TSP)和 $PM_{10}$(空气动力学粒径≤10 μm 的粒子)浓度呈正相关[50]。北京地区沙尘期间可培养细菌浓度也出现了大幅上升,但其与 $PM_{10}$ 浓度并没有表现出相关性[51]。Ho 等[52]也观测到亚洲沙尘事件中,中国台湾地区沙尘期间可培养真菌浓度明显增加,从背景期的 4 839 CFU/$m^3$ 增加到了 6 078 CFU/$m^3$。在黄海沿岸,同样观测到沙尘期间“可培养”微生物的浓度较非沙尘天气增加了 222.8%,而总微生物浓度增加了 118.6%[34]。

目前对于总微生物、耐盐菌等其他类别生物气溶胶的影响研究相对缺乏。Maki 等[53]在日本海以南的沿海城市,研究了亚洲沙尘事件期间总微生物浓度的变化,发现生物气溶胶中总微生物浓度从沙尘前的 $7.5\times10^4$ cells/$m^3$ 迅速增加到了 $2.0\times10^7$ cells/$m^3$,沙尘过后又降到了 $7.7\times10^4$ cells/$m^3$。Yuan 等[51]在北京的研究发现,沙尘期间的总细菌浓度比非沙尘期间高出了 1 个数量级,并且与 $PM_{10}$ 浓度呈显著正相关。李鸿涛等[33]观测到亚洲沙尘期间,兰州和青岛地区的总微生物浓度均呈现大幅上升趋势,兰州较强沙尘期间总微生物浓度升高了 13.8 倍,青岛浮尘期间总微生物浓度升高了 5.42 倍。Tang 等[54]也观测到在亚洲沙尘事件中,中国北部地区总微生物浓度由非沙尘天的 $10^4$~$10^5$ cells/$m^3$ 增加到了沙尘天的 $10^5$~$10^6$ cells/$m^3$。

这些研究显示,不论可培养细菌、真菌还是总微生物浓度,均在沙尘天气下显著增加,但不同地区不同种类微生物的变化相差很大(图 1)。可见,沙尘天气对生物气溶胶中微生物种类及其浓度的影响是一个非常复杂的过程,受到多种因素的影响,天气过程与沙尘源地、强度、沙尘粒子浓度、粒子组分等都会影响生物气溶胶的组成与浓度,要真正理解其中的机制,有必要进一步深入研究。

### 3.2 沙尘天气对生物气溶胶粒径分布的影响

微生物在空气中的存活能力[58]、传输[25]以及在人体呼吸道的沉积[59]等行为与生物气溶胶的粒径、密度和形状密切相关。不同种类的微生物具有不同的粒径分布[34,60,61]。从表 1 可看出,除 Wang 等[67]在中国台湾发现可培养细菌中值粒径在 1.51~1.81 μm 外,非沙尘天气下,细菌、真菌和总微生物主要分布于粗粒径颗粒物中。陆地生物气溶胶中细菌的中值粒径在 2.4~6.6 μm,这与细菌主要附着在粗颗粒物上有关,粗颗粒物可以为细菌提供更好的庇护作用,减少其受紫外线环境暴露的影响,因而有利于微生物的存活[75]。陆地生物气溶胶中真菌多单独悬浮于空气中,其中值粒径在 2.08~4.33 μm[62~66,68,70,71],这与早期研究一致[76]。而有限的研究[72~74]显示,海洋生物气溶胶中细菌和真菌的中值粒径比陆地样品小,分别为 1.89~2.37 和 2 μm。这些研究显示,不论海洋还是陆地生物气溶胶中,空气微生物均主要存在于粗粒子中。

沙尘天气对生物气溶胶的粒径分布同样具有较大影响。Yeo 等[77]在韩国瑞山春季发现,沙尘天气下在 1.1~2.1 μm 粒子上存在真菌孢子,但在非沙尘天气下并未在该粒径段观测到孢子,说明在亚洲沙尘期间有细粒径的真菌孢子悬浮于空气环境中。而 Choi 等[78]在亚洲沙尘期间观察到粒径在 0.6~4.3 μm 的细菌增加很多,但是真菌粒径谱无变化。李鸿涛等[33]研究发现,兰州地区生物气溶胶中总微生物浓度的最高峰值由非沙尘天的大于 7.0 μm 移动到了沙尘天的 1.1~2.1 μm,而青岛地区由非沙尘天的双峰分布转变为沙尘天的粗粒径为主的偏态分布。Polymenakou 等[79]于 2006 年 2 月在地中海东部沿海城市的一次强沙尘过程中发现,不仅载有产芽孢菌的大粒子(>3.3 μm)浓度增加,可吸入粒子浓度也会增加,而且放线菌和拟杆菌属等微生物的浓度随小粒子粒径的减小而增大,其中很大一部分还与引发人类疾病的几种病原微生物有亲缘关系。

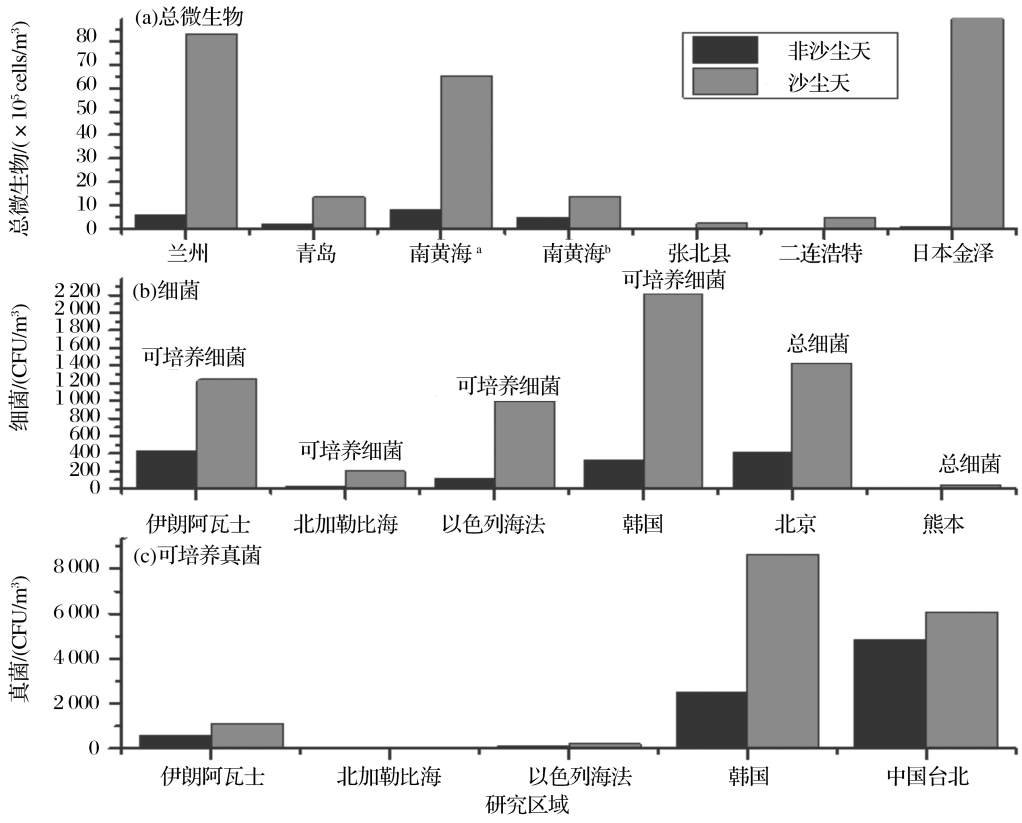



**图 1　全球沙尘期间生物气溶胶的浓度水平(数据来源于参考文献[33,46~48,50~52,54~57])**

**Fig.1　Concentration levels of bioaerosols during global dust period (adapted from references[33,46~48,50~52,54~57])**

a.采样位置为 34.999°N, 122.177°E;b.采样位置为 33.229°N,125.216°E

a.Sampling located at 34.999°N,122.177°E;b.Sampling located at 33.229°N,125.216°E

**表 1　大气生物气溶胶中细菌、真菌和总微生物的中值粒径**

**Table 1　The median particle size of bacteria, fungi and total microbes in atmospheric bioaerosols**

| 研究地区 | 中值粒径/μm | | | 参考文献 |
|---|---|---|---|---|
| | 可培养细菌 | 可培养真菌 | 总微生物 | |
| 青岛 | 陆源:5.22<br>海源:5.71 | 陆源:2.61<br>海源:2.71 | | [62] |
| 青岛 | | | 2.37 | [57] |
| 杭州 | 3.4~3.8 | 2.9~3.0 | | [63] |
| 北京 | 4.59~5.13 | 3.73~4.33 | | [64] |
| 北京西单 | 5.6 | | | |
| 北京丰台 | 6.6 | 3.9 | | [65] |
| 天津塘沽 | 5.5 | | | |
| 中国台湾 | 2.76 | 2.02 | | [66] |
| 中国台湾 | 1.51~1.81 | | | [67] |
| 中国台北 | | 2.3~3.1 | | [68] |
| 美国华盛顿 | 3.2~4.8 | | | [58] |
| 美国俄勒冈州 | 3.93 | | | [69] |
| 英国 | 3~4.48 | 2.08~4.22 | | [70] |
| 新加坡 | 2.4 | 2.46 | | [71] |
| 瑞典 | 2 m 高:2.58~3.75<br>10 m 高: 2.46~3.73 | | | [72] |
| 地中海 | 2.11 | 2 | | [73] |
| 上海至北冰洋航线 | 1.89~2.37 | | | [74] |

可见,不同种类微生物的粒径分布在沙尘天气下的变化是不同的,尚不明确沙尘天气下生物气溶胶粒径分布的变化规律,而且目前的研究较多集中于生物气溶胶中的细菌和真菌,对于总微生物等其他微生物在不同粒径上的分布和浓度变化的关注不够。

## 4　沙尘天气对生物气溶胶中微生物群落结构及优势微生物的影响

微生物群落结构是微生物种群对其外界环境因子的反映,当出现沙尘天气时,气象条件等环境因子会发生改变,生物气溶胶中的微生物群落结构与优势微生物也会发生改变[47,50,51,80~82]。Hara[83]在中国东海的研究发现,沙尘天气下生物气溶胶中的可培养细菌以能形成孢子的细菌为主,此外还有一些则是含有高的鸟嘌呤和胞嘧啶的革兰氏阳性菌,而鸟嘌呤和胞嘧啶的含量越高,细菌的紫外辐射耐受性越强[84]。Fumihisa 等[85]的研究也发现了相似的结果,与土壤中的细菌相比,沙尘携带的生物气溶胶中的细菌紫外辐射耐受性更高,其孢子的紫外辐射

耐受性也要比土壤中的高。这些优势微生物的改变是生物气溶胶可借助沙尘长距离传输的原因之一。

Lee 等[80]研究发现,沙尘天气发生时,微生物的群落结构会发生很大变化,对人体健康有害的类群增多。Chao 等[86]在亚洲沙尘生物气溶胶中发现了非沙尘天未观测到的葡孢霉属和单端孢属。Jeon 等[50]在韩国观察到生物气溶胶中的细菌群落在亚洲沙尘事件中发生了突然改变,这种改变与 $PM_{2.5}$ 化学组成的变化呈现相同趋势,意味着沙尘粒子与群落变化有一定的相关性,但尚不能确定是何种粒子组分影响着微生物群落。Maki 等[53]在日本海以南的沿海城市,发现沙尘期间因为沙尘和海洋气溶胶的输入,沿海的微生物群落结构易发生变化,沙尘事件初始阶段检测到了海洋源的变形菌纲,而沙尘期间 2 种来自中国沙漠的硬壁菌门种为优势菌,沙尘结束后主要为来自局地陆源的巨大芽胞杆菌。韩晨等[87]在青岛的研究显示,沙尘天与晴天生物气溶胶中真菌的物种差异较大,不同沙尘天真菌种类差异较大,但优势菌均为曲霉属菌株,而且沙尘天对人类健康存在潜在危险的产毒真菌数量高于晴天。

也有研究发现,沙尘传输过几百乃至几千公里后,耐盐菌成为生物气溶胶中微生物的典型种类[17,88,89]。Maki 等[88]在敦煌的沙尘粒子中检测到了存活的耐盐菌,DNA 测序显示其与深海中存在的耐盐菌极为相似,推测沙尘沉降是海洋细菌的一个来源。Hua 等[90]的研究也发现了类似的结果,沙尘携带的细菌具有高度的耐盐性。而且,沙尘携带的细菌主要为革兰氏阳性菌,对恶劣环境有更强的耐受力[22,24~25,46,48],在地中海沿岸发现沙尘期间 77% 的细菌是革兰氏阳性菌或革兰氏阳性产孢菌[91]。

综上所述,沙尘事件对空气环境中微生物群落结构影响很大,但是沙尘天气对微生物群落结构的影响是一个非常复杂的过程,加之相关研究缺乏,对沙尘天气下微生物群落结构的变化规律尚不可知,要真正理解沙尘事件对微生物群落结构的影响,需要进一步深入研究。

## 5 沙尘天气对生物气溶胶中微生物活性的影响

微生物活性是指微生物进行新陈代谢活动的强度,其活性水平取决于多种生物、化学和物理因素以及环境营养状况,可用于评估各种干扰过程(如人为活动等)对微生物群落的影响[92,93]。环境样品微生物活性测定主要是通过测定其生理代谢活性水平来实现,目前土壤和水体环境样品中微生物活性测定主要包括 4 类检测技术:碳呼吸、放射性标记物掺入细胞大分子、腺苷能荷(AEC)和酶活性分析[94]。由于空气中微生物的浓度要比土壤、水体等环境中的低很多,微生物活性的分析较为困难,迄今对生物气溶胶中微生物活性的研究仍非常有限。Qi 等[95]提出了利用 FDA 水解法测定生物气溶胶中的微生物活性,该方法可以快速准确地测定微生物的活性水平,并得到了较好的验证。Hara 等[56]在日本的研究发现,沙尘样品中细菌总浓度比非沙尘样品高 1~2 个数量级,但细菌存活率为 16%~40%,低于非沙尘期。Yuan 等[51]在北京的研究也得到了相同结果,细菌的存活率由沙尘前的 64%降到了沙尘中的 32%。

沙尘的长距离传输对细菌存活率有较大影响,也会影响到微生物活性,但目前对沙尘天气下生物气溶胶中的活性水平和分布特征尚未见到报道,更不清楚其区域变化和影响机制。但是,生物气溶胶的环境效应和健康效应很大程度上取决于活性,因此,要全面了解沙尘天气对生物气溶胶性质和分布的影响,就需要了解沙尘天气下微生物的活性水平和分布。

## 6 结论与展望

近年来,对沙尘天气下生物气溶胶的研究取得了较大进展,研究发现沙尘天气下生物气溶胶的浓度较非沙尘天显著增加,粒径谱发生明显改变,生物气溶胶中微生物活性及群落结构都较非沙尘发生很大变化。但是由于沙尘强度、传输途径、影响范围以及局地生物气溶胶的来源等这些影响因素复杂,目前尚不明确沙尘天气对生物气溶胶浓度、粒径分布和群落结构的影响程度和影响机制。将需要进一步深入研究以下问题。

(1)多数研究集中于可培养的细菌或真菌,而对沙尘天气下其他类别生物气溶胶(如总微生物,耐盐细菌、花粉等)的浓度和粒径分布的研究非常缺乏。运用在线检测技术结合离线分析,研究不同类别生物气溶胶的浓度和粒径谱,有助于全面了解沙尘天气下生物气溶胶的环境、气候和健康效应。

(2)目前对沙尘天下生物气溶胶的研究还很有限,尚未明确不同强度的沙尘(浮尘、扬沙等)天气下生物气溶胶浓度、粒径谱、微生物群落结构和优势微生物等特性的变化规律。需要在更大范围内系统研究不同沙尘事件下生物气溶胶的性质和分布,才能理解长距离传输沙尘对对生物气溶胶的影响

机制。

(3)尽管目前发现生物气溶胶浓度和特性的改变与温度、相对湿度以及沙尘等特殊天气有关,但仍不能揭示其控制因素和影响机制。空气中生物气溶胶受到气象条件、大气过程、气溶胶化学组成、污染气体、局地源等多种因素的综合影响,除了现场观测,还需要室内单因子实验确定主要影响因素。

(4)目前有关微生物活性等生物气溶胶特性的研究匮乏,更缺乏沙尘事件对微生物活性影响的了解。以后仍需要建立灵敏测定生物气溶胶微生物活性、毒理性等生物气溶胶特性的方法,进一步深入研究生物气溶胶环境和健康效用。

(5)沙尘携带的生物气溶胶不仅影响到下风向生物气溶胶的性质,而且还会在一定天气条件下传输并沉降到海洋,影响海洋生态和环境,但是对其影响尚不清楚,亟需研究。

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# Impact of Dust Events on the Concentration, Property and Distribution of Atmospheric Bioaerosols*

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**Abstract**: Atmospheric bioaerosols have great impact on the global climate, air quality, atmospheric process and human health. The dust events have a role in transporting bioaerosols and affecteing the concentration and property of bioaerosols in the downwind area by facilitating long-distance dispersal events every year. This paper reviewed the study progress on the concentration, characteristics and distribution of bioaerosols in dust weather. The references showed that the ratio of different kind of bioaerosols changed in dust weather with the changing of contribution of bacteria and fungi. The concentration of cultural bacteria, fungi and the total microbes increased on dust days. However, the increase ratio was different for different microbes in different areas. Microbes in bioaerosols mainly distributed in coarse particles; the size distribution of bioaerosols was affected greatly by dust events with different variation for different kinds of bioaerosols. The microbial community and predominant species of microorganism in bioaerosols changed in dust weather. The impact and mechanism of dust on the concentration, size distribution, microbial community and activity of bioaerosols need to be studied further.

**Key words**: Dust; Bioaerosols; Microbes; Size distribution; Microbial community.

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