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气载藻类的空气传播：分布动态、环境驱动因素与健康风险*[1]

王曼斯[1,2,3]，阳　振[1,2]，史小丽[1,2,3]，张　民[1,2,3**]

（1：中国科学院南京地理与湖泊研究所，湖泊与流域水安全重点实验室，南京 211135）

（2：中国科学院南京地理与湖泊研究所，湖泊与环境国家重点实验室，南京 211135）

（3：中国科学院大学南京学院，南京 211135）

摘要：水体中的藻类可随着水汽界面破碎的气泡进入空气，并以气溶胶为载体在大气中传播。这不但是一种重要的藻类种群扩散方式，影响着周边水体的种群结构，同时空气中有害藻类的增多也会导致较大的健康风险。目前，人们对于气载藻类的认知尚显不足，且主要见于国外文献报道。本文系统梳理了气载藻类在空气中的分布特征，包括它们的主要种群组成、季节性变化和昼夜变化模式，阐述了温度、湿度、风速等影响气载藻类生存和传播的环境因素，介绍了气溶胶中的有害藻类对人类健康的影响。最后，针对当前研究的不足之处，本文建议未来的研究应重点关注气载藻类的定殖动态，了解它们在空气中的存活和繁殖情况；汇源识别，确定气载藻类的主要来源与沉积区域；风险评估，预警气载藻类及藻毒素气溶胶对于人类健康的长期影响。

关键词：气载藻类；藻毒素；传播方式；环境因子

Airborne Propagation of Airborne Algae: Distribution Dynamics, Environmental Driving Factors and Health Risks

Mansi Wang[1,2,3], Zhen Yang [1,2], Xiaoli Shi[1,2,3], Min Zhang [1,2,3**],

(1: *Key Laboratory of Lake and Watershed Science for Water Security, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing 211135, China*)

(2: State Key Laboratory of Lake Science and Environment, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing 211135, China)

(3: Nanjing School, University of Chinese Academy of Sciences, Nanjing 211135, China)

Abstract: Algae present in aquatic ecosystems have the capacity to enter the atmosphere through the process of bubble bursting at the water-air interface. Following this initial entry, the algae can then be disseminated via the process of aerosol transmission. This process is of critical importance in facilitating algal dispersal, thereby influencing population structures in adjacent water bodies. However, it should be noted that this process also poses significant health risks due to the increased presence of harmful algal species in the air. The current state of knowledge regarding airborne algae remains limited, with the majority of extant research documented in international literature. This review systematically examines the distribution characteristics of airborne algae, encompassing dominant taxa, seasonal fluctuations, and diurnal variation patterns. Furthermore, it provides a comprehensive overview of the environmental determinants that govern algal survival and atmospheric transport, including temperature, humidity, and wind speed. A particular emphasis is placed on the health implications that arise from the presence of aerosolized harmful algae and cyanotoxins. In order to address the existing knowledge gaps, future research should prioritise three critical domains:

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** 通信作者；E-mail: mzhang@niglas.ac.cn

The first research question concerns the dynamics of colonisation, with the objective of investigating the viability and reproductive potential of airborne algae in atmospheric environments. The second research question pertains to the identification of source-sink dynamics, with the aim of tracing emission hotspots and deposition patterns. The third research question focuses on the development of comprehensive risk assessment frameworks, with the objective of evaluating the long-term health impacts of algal aerosols and establishing early warning systems. The proposed directions are intended to facilitate a more profound comprehension of the subject matter, thereby providing a foundation for the development of evidence-based environmental management strategies.
Keywords: Airborne algae, algal toxins, Transmission Modes, Environmental Factors

气溶胶是由悬浮于气体介质中的固态或液态颗粒组成的气态分散体系，通常含有细菌（包括古细菌）、真菌孢子、花粉、病毒及藻类等微生物，其粒径范围从纳米级到数十微米不等[1]。学者将脱离液态介质后以气溶胶为载体，并保留代谢活性或复苏潜力的藻类生物称为“气载藻类（Airborne algae）”，它们主要来源于风应力、破碎波作用或人类活动（如划船）等物理干扰引起的水气界面气泡破碎[2, 3]。当水气界面上的气泡破碎时，水体表层的藻类释放至空气中，并以空气作为传播媒介扩散至邻近水域上空，最终通过降水或沉降等途径重新定殖，从而影响周边水体的藻类群落结构。气载藻类参与地球物质循环的各个过程，且通过空气扩散促进了大部分藻类在全球的广泛分布；同时，扩散至空气中的产毒藻类及藻毒素也会导致人类呼吸道疾病加重、引发皮肤疾病等健康危害。

随着 20 世纪全球水体富营养化与气候变化的影响，海洋、湖泊等水体中的藻类生物量显著升高，赤潮或水华在许多水域频繁暴发，导致释放到大气中的藻类越来越多。这一方面提升了藻类种群在空间上的扩散能力，从而使它们对周围水体的影响更为显著；另一方面，部分产毒藻类及其产生的藻毒素在空气中的含量也随之增加，对人类的身体健康造成了一定的威胁。近期有知名学者提出了的“空气富营养化”的新概念[4]，呼吁大家关注气载藻类及其生物毒素所带来的健康风险问题。本文基于国内外对气载藻类的研究成果，对气载藻类起源及种类、形成过程及时空分布、传播途径及影响因素以及可能对人类健康造成的风险等方面进行了梳理，并对未来国内的研究趋势做了展望。

1 气载藻类的起源及常见种类

自 1844 年 Ehrenberg 首次从空气尘埃中鉴定出 18 种硅藻以来，气载藻类的存在性得到科学确认[5]，van Overeem 开创性培养实验，标志着该领域研究体系化的开端[6]。至 1996 年，KJ 发表文章表示气载藻类的微观大小以及空气传播媒介促进了大多数藻类在全球的广泛分布[7]。百余年的研究历程逐步揭示：气载藻类的扩散传播并非孤立的环境现象，而是由生物特性与大气动力学共同塑造的跨界传输系统。

经统计，2011 年之前在相关文献中共发现 353 个不同的气载藻类群（隶属 175 属），其中大多数属为蓝藻（37.4%）和绿藻（35.4%），其中有 52 种分类群被确认为对人类健康构成潜在威胁，其中 38 种已被证明会诱发健康问题，另有 14 种被证实会在自然环境中产生毒素[8]。从地区来看，温带地区的气载藻类群落主要为绿藻门[9, 10]，而热带地区则以蓝藻门为主[9]。其他被鉴定到的分类类群还包括硅藻门(15.3%)、链藻门(4%)、甲藻门、裸藻门、附藻门和隐藻门。本文对 2011 年后的相关文献进行了收集整理（表 1），结果进一步证实气载藻类广泛存在于各类生境。其中蓝藻门色球藻属以及绿藻门小球藻属分布较为广泛，在海洋及陆地地区均有出现[11-13]。例如，在亚得里亚海的大气样本中，蓝藻门为优势藻类类群[14]；在波罗的海西南部地区的空气样本中，蓝藻及绿藻的相对丰度高达 49%和 48%[15]；此外，在沿海地区，蓝藻门也是空气中占比较高的门类，相对丰度可达 18.8 - 26.9%[16, 17]。

表 1 已有文献报道的气载藻类（2011 年以来）

Tab.1 The aerosol algae that have been reported in the existing literature since 2011

栖息地	传播载体	采样地点	分类	参考文献
海洋、陆地	空气	波罗的海西南部	蓝藻门/ 色球藻属 集胞藻属 隐球藻属 微囊藻属 绿藻门/ 小球藻属 裂丝藻属 硅藻门/ 褐指藻属 舟形藻属	[15]
海洋	空气	亚得里亚海	蓝藻门/ 粘球藻属 乌龙藻属 小雪藻属 集胞藻属 色球藻属 细鞘丝藻属 绿藻门/ 小球藻属 裂丝藻属 片球藻属 绿球藻属 硅藻门/ 楔形藻属 双眉藻属	[14]
海洋	空气	北海-波罗的海	蓝藻门/	[18]
沿海	空气	波罗的海沿岸地区	蓝藻门/ 念珠藻科 节球藻属 色球藻属 集胞藻属 隐球藻属 假鱼腥藻属 席藻属 隐杆藻属 色球藻属 绿藻门/ 小球藻属 裂丝藻属 片球藻属 绿球藻属	[19]
沿海	空气	中国沿海地区	蓝藻门/	[16]
沿海	空气	地中海中部沿海地区	蓝藻门/	[17]
沿海	空气	北卡罗来纳州沿海	蓝藻门/ 鱼腥藻属 假鱼腥藻属 长胞藻属 束丝藻属	[20]

			微囊藻属	
陆地	空气	雅典	蓝藻门/	[21]
陆地	空气	北京	蓝藻门/	[22, 23]
陆地	空气	长沙	蓝藻门/	[24]
陆地	空气	宾夕法尼亚	蓝藻门/	[25]
陆地	空气	斯洛伐克西南部	蓝藻门/ 念珠藻科 色球藻属 席藻属 绿藻门/ 小球藻属 双胞藻属 裂丝藻属 克里藻属 片球藻属	[26]
陆地	空气	马来西亚吉隆坡室内	硅藻门/ 蓝藻门/ 色球藻科 念珠藻科 席藻科 颤藻科 假鱼腥藻属 绿藻门/ 共球藻纲 绿球藻科 栅藻科 丝藻科 衣藻属	[27]
陆地	空气	南非约翰内斯堡	硅藻门/ 舟形藻属 蓝藻门/ 绿藻门/ 共球藻纲	[28]
极地	空气	南极	小球藻目 衣藻目 溪菜目 石莼目 丝藻目	[29]
高原	空气	喜马拉雅	蓝藻门/	[30]

2 气载藻类的形成过程及时空分布特征

2.1 气载藻类的形成过程

液滴的生成是藻类从水体生态系统向空气扩散的主要途径[3, 31, 32]。根据其生成机制的不同，可产生不同类型的液滴（如浪花液滴、薄膜液滴和喷射液滴）。当风速超过 7-11 m/s 时，海面破碎波通过风力摩擦作用会产生直径大于 40 μm 的浪花液滴[33]。而由波浪、降雨、船舶航行或水体气体过饱和等因素引起的气泡破裂过程，则会形成向不同方向溅射的薄膜液滴（1-10 μm）和垂直喷射的喷射液滴（6-100 μm）。各类型液滴的形成会导致水体表面藻类等生物进一步富集，进而通过风输送到空气中形成气载藻类[34, 35]。

风浪[33]、扬尘[36]、水汽挥发[2, 10]及人类活动干扰[27]等过程共同驱动水生藻类向大气扩散。水华发生期间，气载藻类（特别是小粒径藻类）沿水面主导风向向邻近陆地迁移[37-40]，若风速较大则会进一步增加水体表面的波浪活动，从而加剧藻类的气溶胶化，另外风速的升高一定程度上延长了气载藻类的悬浮时间，影响

了藻类的传播距离[32, 41-43]。这种跨介质传输过程的高度环境敏感性，一方面受到风速影响，另一方面也受到温度调控。水温升高会显著增加气泡破裂频率，促进含活性藻类的气溶胶的生成[44, 45]。除了物理环境因素，气载藻类本身的生物学特性也塑造了其扩散模式。体积较小的藻类颗粒因具有更良好的大气适应性，进而成为跨区域扩散的优势类群，此外气载藻类还显现出按地域传播的特性[46]，这种粒径选择效应与地理传播特征反映了局地气候条件、水体健康状况以及生物特性的相互作用，但具体三者之间如何耦合尚不清楚。

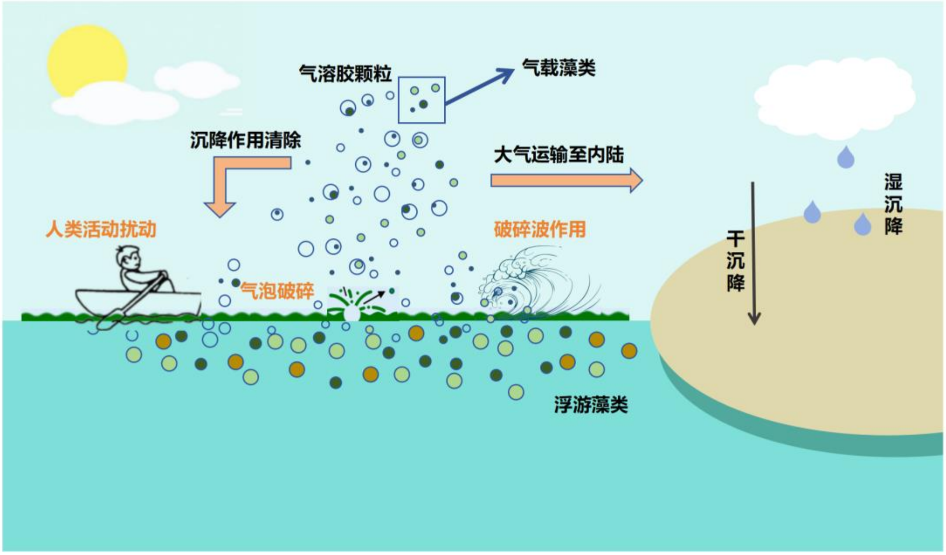

图 1 气载藻类的形成过程及传播途径示意图

Fig.1 Schematic diagram of the formation process and transmission routes of airborne algae

2.2 气载藻类的时空分布特征

2.2.1 气载藻类的空间分布 不同地区的研究结果表明，微生物核心群落的形成与区域环境条件密切相关，采样季节、采样地点、大气污染水平以及人类活动丰富度等因素均会影响空气微生物群落的多样性和组成。在城市及郊区的样本中，除了常见微生物菌门外，还检测到蓝藻门等常见藻类[47-49]，且各门类在城市及郊区样本中的占比存在差异。例如，在雅典、北京、长沙等城市大气样本中均有检测到蓝藻门，且蓝藻门有时被认定为优势菌门[21-24]；在希腊空气样本中，鉴定到的气载藻类以硅藻为主导（42%），而蓝藻仅占 20%[14]；然而，在 6 月的雅典空气样本中，蓝藻门则进一步成为罕见菌门（<1%）[21]，这表明空气中的藻类多样性会随采样地点和时间的变化而变化。此外，空气污染程度也是驱动气载藻类多样性变化的重要因素[22, 24, 50-52]，在人类活动密集的城市与人类活动较少的郊区，空气样本的群落组成有明显差异，在郊区空气样本中蓝藻门丰度显著高于空气污染相对严重的城市站点[25]。气载藻类不仅存在于开阔环境的空气中，在室内环境乃至空调系统中，也检测出含蓝藻在内的藻类种群[27]。建筑环境空气中的微生物通常来源于人类、宠物、空调系统等八大类，其中人类活动则是影响室内环境藻类扩散的重要因素[28]。此外，在极地、高海拔等气候极端地域（如南极、喜马拉雅高原）大气样本中，也检测到绿藻门、蓝藻门、裸藻门等多个分类群，这一定程度上表明陆地和海洋之间存在强烈的大气交换[29, 30, 53]。

2.2.2 气载藻类的季节与昼夜变化 气载藻类的组成与丰度受藻类来源、藻类释放及大气扩散三方面影响，在季节及昼夜尺度上呈现一定变化。例如，西班牙西南部空气样本显示藻类浓度在春季至初夏期间明显增高[13]，而波罗的海西南部空气样本检测结果则显示藻类多样性与丰度在冬末至春季微增，印度 Varanasi 市空气样本研究则显示蓝藻在温暖季节占主导，绿藻则在寒冷季节丰度较高，硅藻全年保持稳定，仅在初冬时期数量较少[11, 12]。这表明不同地区的温度变化及空气动力学差异可能会导致气载藻类的丰度呈现不同的季节规律[15]。除环境因素的影响外，不同藻类对于大气温度的响应也不同[54]，蓝藻易于在高日照条件下被气溶胶化，而绿藻则多在无日照的低温夜间呈现释放高峰，形成“昼蓝夜绿”的群落分布规律[55]。在群落

数量方面，西班牙 Badajoz 市的大气观测发现，12:00-24:00 时段藻类丰度达到 24:00-12:00 的两倍水平，峰值集中在傍晚（17:00-20:00），谷值则出现在后半夜至凌晨（01:00-7:00）[13]；中欧温带内陆地区的监测数据亦显示藻类在白天的丰度增加，多数藻类类群在 14:00-16:00 时段达到日间最大丰度[26]，但受地理特征与气象因子的区域性影响，多数区域缺乏普适性昼夜规律[8]。

3 气载藻类的传播途径及受气候气象影响

3.1 气载藻类的大气传播

气载藻类可在近地面大气环境中持久悬浮[56]，其扩散迁移过程主要受到自然媒介的物理动力学控制，其中风力与降水作用是气载藻类跨越地理屏障的核心动力。在适当气象条件下，藻类细胞可依附于尘埃颗粒或气溶胶表面[15, 57]，实现公里级至跨半球尺度的远距离迁移[58, 59]。无论藻类是来自海洋还是地表，大气运动都会影响它们的传播，而蓝藻等强适应型气载藻类则具有自发源地向外扩散上千公里的能力[60]。据模型测算，海洋界面释放的气溶胶组分中约有 10%可在空气中停留超过 4 天，并可传播超 10000 km[61]；墨西哥湾沿岸 320 km 处的实地监测结果显示有 93%的时段监测到海洋喷雾气溶胶（Sea spray aerosols, SSA）[62]。湖泊的调查案例显示，源自北美五大湖的湖泊喷雾气溶胶（Lake spray aerosol, LSA）虽主要聚集于源区周边，但部分 LSA 可输送至 1000 km 外[63]。据预测模型推算，五大湖区气溶胶排放可使其北部偏远地区的地表气溶胶浓度提高约 20%，其它地区提高约 5%[64]。高风速情况下，五大湖的水面 LSA 扩散可使其周围部分地区的大颗粒气溶胶数量增加 19 倍[63]。与模型预测结果相似，加拿大 Hudson 湾实测数据显示 SSA 和五大湖 LSA 分别促进了密歇根州北部（>700 km）和农村地区（>25 km）大气气溶胶含量的增加[65]。气载运输在微生物扩散、水生态系统多样性维持等方面发挥了重要作用[66]，早期观察表明，温度和风速是影响气载藻类丰度最重要的两个因素[67, 68]，而相对湿度、降雨量、风速对气载藻类多样性亦有重要影响[12]。利用全球大气模型对藻类气溶胶的扩散概率进行研究，结果显示小粒径藻类凭借较高丰度、较长停留时间，在远程传输中占优[58]，但气载藻类的生存能力也会随着传输距离的增加而逐渐减弱[69]。相较于水生环境，气载藻类展现出对干燥、低温（＜0℃）等极端条件的耐受机制，具有较强的环境适应性，同时许多气载藻类还表现出良好的定殖潜力[70]，但其后期的定殖以及定殖后的群落结构则会受到定殖生境的营养成分和盐度的影响[71]。

3.2 气载藻类的雨水传播

作为大气传输的终止环节，降水过程通过湿沉降机制实现气载藻类向地表/水体界面的定向输移[72-75]。与干沉降相比，湿沉降不仅缩短了藻类在大气中的暴露时间，更有效维持了藻类的生理活性[69, 76]，对大气和陆地生态系统的藻类多样性具有重要作用[77-79]，同时也对环境和公共卫生存在潜在影响[80-82]。不同降水类型中的藻类群落存在显著差异，这种空间差异在全球不同气候区得到印证，例如我国北京、上海等特大都市的雨水样本中藻类群落呈现显著季节性特征，同季降水样本的群落相似性较高[83, 84]；而法国中部云层则长期以蓝藻、绿藻为优势类群[85]。以上例子均证实不同地区雨水样本中的藻类群落存在差异，且有研究表明这种藻类群落结构的差异主要受雨水离子组分和 $PM_{2.5}$ 浓度调控[86]。此外，雨水中的藻类同时还具有二次释放潜力，其通过雨滴飞溅、拍打可重新进入大气[87]，但同时降雨的冲刷效应（藻类以凝结核形态伴随雨滴下落）也会去除空气中的藻类，其中暴雨事件对 4-15 μm 的藻类清除效率尤为显著[88]，实测数据显示雨后空气藻类浓度可骤降 87%[89]。由此可知，降水对气载藻类具有双向调节功能：既作为地表输入媒介促进藻类扩散，亦可通过湿沉降机制降低气载藻类浓度。然而，受雨水介质中藻类群落结构多样化以及气候变化、人类活动干扰等多种因子的影响，导致准确定量评估雨水中藻类对生态系统和公共卫生安全的潜在影响仍比较困难。

3.3 气载藻类受气候气象的影响

藻类在空气中的扩散受多种环境因子的影响[90]，目前这些环境因子对气载藻类生存和扩散的影响机制尚不清楚[8, 54]。风速、温度、湿度是气载藻类动态变化的核心环境要素，但其耦合作用机制仍需系统的解析。风速主要通过动力学效应和藻源激活两种方式影响气载藻类的扩散传播。众所周知，空气中颗粒数量通常与风速有关，风速增加则颗粒数量相应减少[91]，相较于空气中的花粉颗粒、真菌孢子，风速对藻类扩

散的影响更大[92]。有研究认为风速和风向是对 SSA 形成影响最大的气象因子，含有藻类颗粒的 SSA 数量浓度与海洋边界层上风速大小呈现较好的相关性[93]。当风力作用将水体表面的藻类颗粒扩散至空气中，藻类在空气中的丰度和生物量则进一步受到气温的影响[48]。就陆地城市而言，随着气温的变化，空气中气载藻类的含量呈现出明显的季节变化[94]，但采样地点不同可能导致截然相反的结果，例如在希腊 Chania 市的研究表明，受温度及太阳辐射的影响，暖季时期微生物的浓度和种类丰富度都较低，而在希腊 Thessaloniki 市的调查结果则显示暖季时期空气中的生物量最高。与藻类生物量不同，气载藻类的物种丰富程度则受到相对湿度的调控。空气的相对湿度（RH）对气载藻类初始存活能力具有显著影响，有研究表明真核气载藻类的初始存活能力与 RH 呈正相关，并在 94 %RH 时展现出最佳存活率[95]，这表明高 RH 更利于气载藻类的存活，并在空气中展现出较高的物种多样性，但高 RH 同时也将增加气载藻类的沉降速率，因此在 RH 较高时，空气中的藻类呈现出“多样性高，相对丰度低”的特点[12]。这意味着即使其它因素处于最佳状态，高 RH 仍可能不利于空气中的藻类浓度增加[13]，相反在 RH 较低的晴朗天气，藻类更易发生剥落而被吹到大气中，从而增加大气中的藻类丰度[9]。

此外，沙尘事件、雾和霾等特殊天气条件均会影响空气中藻类的浓度和丰度[96]。雾可能会提高气载藻类的生存能力并促进它们沉积[97]，沙尘天气蓝藻的相对丰度有所增加，则暗示了粉尘对空气中藻类浓度存在促进作用[98]。有研究认为大气 PM 中的化学成分/污染物是显著改变气载藻类浓度和群落组成的关键因素[99]，空气中轻微的苯并(a)芘污染也可能促进空气中藻类的生长[100]。此外，PM 浓度(洁净空气与雾霾)以及 PM 粒径也会影响气载藻类的群落结构[101]，气载藻类丰度可能首先随着空气中 PM 积累浓度的增加而升高，并在达到严重雾霾的污染条件下开始减少[102]。

4 气载藻类的抗逆适应机制与定殖特性

大气生物群系受到紫外线辐射、干旱、低温、氧化应激和缺乏基本营养物质等多种胁迫因素的影响，这些胁迫因素使得大气中的生物产生了进化压力，并在很大程度上影响其生物多样性[103, 104]。而气载藻类跨区域定殖的成功率主要取决于它们在长距离传输过程中的耐受能力，环境因子如温度梯度、盐度变化及营养供给水平等均是限制它们生存扩散的关键要素[105, 106]。为应对大气环境中极端干燥与强紫外线暴露，不同藻类演化出多样化的适应机制：蓝藻通过合成类胡萝卜素（CAR）吸收 UV-B 波段辐射[107]，并利用其他化合物替代营养物质（C、N）来源[108]；单星藻、栅藻等类群形成多层抗紫外线保护结构[109]；一些地衣共生藻类则通过调控胞外聚合物质（EPS）相关蛋白活性提升脱水耐受力，同时调节多糖裂解过程以增强细胞壁柔韧性，从而抵御干燥环境导致的机械损伤；此外，色素谱系调节策略和阶段性休眠机制也是藻类应对极端环境的重要生存策略[110, 111]。

就空气中的藻类而言，环境胁迫适应能力强的气载藻类往往占据优势，其中源自陆地的藻类相较于水生藻类表现出更优的大气环境适应特性[95]。早在 1960 年代初期，就有研究证实一些风力传播的藻类包囊可在无菌水环境中复苏[112]，后续研究进一步发现尽管多数气载藻类在空气传播过程中处于低活性状态，但其在不同海拔高度（城市建筑物立面[113]到偏远地区[114]）和各类生境（水箱[8]、室内表面[115]及自然陆地[116]）中均能保持生存潜力，并且在沉降至适宜水体后恢复活性[60, 117-119]。关于定殖模式，目前虽未形成普适性理论，但区域性研究已发现特定规律。典型实例来自 Genitsaris 团队的水箱实验[120]，其观察到“异养型微小鞭毛藻→绿藻”的演替序列，其中优势绿藻（小球藻、栅藻）兼具淡水广布性和大气传播适应性。与此相呼应，地中海地区的长期监测显示，暴露于河岸环境的收集装置内绿藻相对丰度持续占优，其定殖效率显著高于硅藻与蓝藻[121]。这些案例共同表明，气载藻类的定殖过程存在类群特异性，其模式可能受源地群落组成与局地环境因子的双重调控。

5 气载藻类对人体健康的影响

5.1 藻类毒素的气溶胶化及其环境影响因子

众所周知，一些藻类能够产生藻毒素，且藻毒素的疏水性特征使其更易于气溶胶化并随风吹至岸上[8, 14, 27, 122-124]。在产毒类群分类方面，海洋生态系统以甲藻门（Dinophyta）为主，可产生腹泻性贝类毒素（DSP）、麻痹性贝类毒素（PSP）、神经性贝类毒素（NSP）及雪卡毒素（CFP）等多种毒素[125, 126]，部分红藻、绿

藻、硅藻和附生藻类也具有产毒能力[127]。淡水生态系统中，产毒藻类以蓝藻门（Cyanophyta）为主，包括微囊藻、长孢藻、拟柱孢藻和颤藻等属，其产生的微囊藻毒素（MC）、鱼腥藻毒素（ATX）及拟柱孢藻毒素（CYN）等是淡水环境中常见的藻毒素种类。监测数据显示，在佛罗里达赤潮发生期间，水样中短裸甲藻毒素浓度为 5-10 μg/L，而赤潮气溶胶中对应的短裸甲藻毒素浓度可达 21-39 ng/m³[128]，且距离海滩 4.2 km 以及距离海岸线 1.6 km 处仍可检测到短裸甲藻毒素[129]，这意味着离开海滩并不能完全避免藻毒素的环境暴露。对美国 St. Marys 湖采集的 PM2.5 样品检测发现，含有最高气溶胶化微囊藻毒素浓度的 PM 粒径分数范围为 0.44-2.5 μm[130]，微囊藻毒素浓度达 156 pg/m³，这接近人类鼻腔微囊藻毒素的耐受日摄入量[4]。一些列研究证明淡水藻毒素可以气溶胶化[131-133]，但藻毒素各类同源物并不会均匀的从淡水系统向气溶胶相转移，藻毒素的气溶胶化主要依赖于其疏水性[134]，具有疏水特性的藻毒素更容易在气溶胶颗粒中富集，因此更容易向气溶胶相转移。此外在迁移过程中，大气中的藻毒素还会经历光解（主要作用于 PAR、UV-A 和 UV-B 波段）、颗粒有机物吸附及微生物降解等消减过程[135]。因此，需要进一步的环境测量，考虑影响微囊藻毒素和其他气溶胶化污染物的其他因素，以全面评估藻毒素气溶胶对环境和公众的影响。

5.2 藻毒素气溶胶对人类健康的潜在影响

已有研究证实含有短裸甲藻毒素、微囊藻毒素等成分的毒素气溶胶与多种急慢性人类疾病存在关联[136-139]。动物毒理实验发现，暴露于短裸甲藻毒素 5 天后的大鼠体重明显低于对照值；吸入短裸甲藻毒素后的绵羊支气管收缩效应剧烈，并引发呼吸系统异常反应[140-142]。在实地观察中，有害藻类水华频发区域的游客和救生员常出现呼吸道症状[143, 144]，而哮喘患者暴露在赤潮毒素气溶胶 1h 即可导致呼吸道症状加重，并对呼吸功能产生长达数天的抑制[145]。即使暴露在极低浓度的藻毒素气溶胶中，也会对哮喘患者的健康造成不利影响，这表明气载藻毒素诱导的生物反应阈值较低[146, 147]。除赤潮产生的短裸甲藻毒素外，微囊藻毒素也会导致慢性鼻炎患者的过敏性反应[148]，微囊藻毒素可使人类气道上皮细胞产生促炎信号分子，改变细胞外基质（ECM）蛋白相关基因的表达，从而进一步诱导诱导炎症反应加剧慢性或急性疾病的产生[149]。进一步研究发现赤潮气溶胶颗粒粒径主要分布在 6-12 μm，常沉积于上呼吸道，气载蓝藻在上呼吸道(92.20%)和中央气道(79.31%)中也有较高的出现频率，这可能是造成救生员等海边工作人群的呼吸道疾病的重要原因[150, 151]。通过鼻拭子检测发现，蓝藻水华期间高达 95%的受试者鼻腔内微囊藻毒素浓度高于检测限[131, 152]，因此相较于水体接触，吸入藻毒素气溶胶更可能导致哮喘患者等敏感人群的呼吸道疾病[151]。

除呼吸道疾病外，气载藻类及相关毒素还会引起皮肤及肌肉僵化等方面的疾病。蓝藻培养物皮肤贴片的实验结果显示，贴上贴片 24h 后，约有 20%的志愿者出现轻微皮肤过敏反应[153]。此外，蓝藻产生的四类毒素中，神经毒素 β-N-甲基氨基-L-丙氨酸（BMAA）已被确认为是导致肌萎缩性侧索硬化症（ALS）的重要环境风险因子[154-156]，流行病学研究表明居住在水华发生区域的人群，由于长期暴露于蓝藻神经毒素，可能会导致 ALS 及神经退行性疾病[157, 158]，并产生相应的嗅觉功能障碍[159]。除 BMAA 外，拟柱孢藻毒素（CYN）也是一种强效细胞毒素，除了对人类肝肾表现出明显毒性外，它也会破坏气道上皮完整性并干扰细胞信号转导，对呼吸道表现出潜在的毒性[160]。

6 展望

近年来针对藻类水华和赤潮的发生机制与防控治理研究持续发展，进而扩展至水体表面藻类气溶胶化及扩散的研究。然而相较于对水体中的藻类，对气载藻类研究还尚显不足。本文梳理了目前国内外关于气载藻类的种群及生存特性，传播方式及影响传播的环境因子，对人类的健康影响等方面的研究成果，但解释藻类在空气中的传播扩散以及相关的健康风险是一个复杂的问题。关于气载藻类种群、传输与健康风险的研究，还有以下方面需要深入探讨。

6.1 气载藻类在空气中的生存及定殖特性

藻类在空气中的传播扩散以及生存特性具有其独特的复杂性，目前尚不清楚这些气载藻类如何能够如此快速地扩散，以及环境参数在多大程度上有利于扩散的加速，因此，评估这些变化将在多大程度上影响大气循环和气载藻类的扩散效率非常重要，研究气载藻类的大气循环过程也将为进一步探索藻类生态学以及藻类在大气中的生存和繁殖提供重要的机会。此外，气载藻类在新栖息地的定殖动态，以及新栖息地环境差异对定殖过程的影响也需要深入研究。

6.2 气载藻类的源汇分析及扩散过程预测

气载藻类在空气中的传播扩散表明藻类水华的环境影响可由水华发生地向外扩散。目前，空气中气载藻类的源解析以及水华发生地的藻类向何区域扩散、定殖等问题仍缺乏了解，因此在气载藻类生存扩散研究的方面，有必要对其扩散路径进行建模，将原位监测与模型模拟相结合，开展生态学、气象学等多学科合作，以准确识别气载藻类源、汇，为预测其扩散过程和生态风险提供支撑。

6.3 藻毒素气溶胶引起的的急性和慢性暴露风险评估

在对人体健康影响方面，藻毒素的研究仍然受到有限的暴露评估方法和缺乏可靠的流行病学研究设计的阻碍。有证据已表明，在距离源头数十公里的地方仍可检测到雾化毒素，这意味着很大一部分人群可能面临急性和慢性暴露的风险。气候变化和富营养化导致有害藻类水华日益增多，使得有毒藻类及藻毒素相应增加，威胁人类健康。因此，追切需要深入研究气溶胶中藻毒素和其它有害成分的环境浓度，以及人体对它们的耐受风险，以确定是否应实施藻毒素吸入指南，并建立有效的干预措施。

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