Bulletin of Regional Natural History (BORNH)

Vol.3, no.1, 2023
Mini Review

Bulletin of Regional Natural History

Formerly Bollettino della Società dei Naturalisti in Napoli

Aerobiology of Algae and Cyanobacteria

Sharath Chandra Thota

DOI https://doi.org/10.6093/2724-4393/10003

***Correspondence:**
sharathota25@gmail.com

https://orcid.org/0000-0001-7343-0632

Affiliation:
Villa 59, Ramky Enclave, Warangal, Telangana state, India.

Conflict of Interest: The author declares that he has no conflict of interest.

Financial Disclosure Statement: The author declares that no specific funding was received for this work.

Submitted: 15 Feb. 2023
Revised: 20 April 2023
Accepted: 25 April 2023

Associate Editor: Antonino Pollio

Abstract

Algae and cyanobacteria are considered the major groups of primary producers on this planet. Many food webs begin with these microorganisms, making their presence as primary producers vital for creating a perfect ecosystem in the air and sustaining their dependents. These microbes in the air can be both harmful and useful due to their unique metabolic pathways (photosynthesis) and metabolites (toxins). Additionally, certain activities can have global climate impacts (such as ice nucleation). Atmospheric microbiology has been an understudied area of biodiversity. This review complies a few studies on the diversity and distribution of atmospheric primary producers such as algae and cyanobacteria.

Keywords: Atmosphere, troposphere, stratosphere, microalgae, cyanobacteria

Riassunto

Le alghe e i cianobatteri sono considerati i principali gruppi di produttori primari del pianeta. Molte reti alimentari iniziano con questi microrganismi e la loro presenza risulta vitale per creare un ecosistema anche nell'aria e per sostenere gli altri organismi che dipendono da loro. I microrganismi fototrofi che vivono nell'aria possono essere sia dannosi che utili, grazie alle loro vie metaboliche peculiari (fotosintesi) e ai loro metaboliti (tossine). Inoltre, alcune attività metaboliche connesse alla loro presenza possono avere un impatto sul clima globale (come la nucleazione del ghiaccio). La microbiologia atmosferica è un settore poco studiato della biodiversità microbica; questa review raccoglie alcuni studi sulla diversità dei produttori primari atmosferici e sulla loro distribuzione nei vari strati dell'atmosfera.

Parole chiave: Atmosfera, troposfera, stratosfera, microalghe, cianobatteri.

How to cite

S.C. Thota (2023). Aerobiology of Algae and Cyanobacteria. Bulletin of Regional Natural History (BORNH), Bollettino della Società dei Naturalisti in Napoli. Vol. 3, n. 1, pp. 53 - 64 ISSN: 2724-4393.

Introduction

An Atmosphere is a layer of gases that envelop a planet and are in place by the gravity of the planetary body. The atmosphere of Earth is composed of nitrogen (78%), oxygen (21%), argon (0.9%), carbon dioxide (0.04%), and trace gases. the atmospheric nitrogen can be converted into N-reduced compounds by natural processes, such as lightning or biological nitrogen fixation by bacteria (Mus et al., 2016). These processes produce molecules needful for nucleotide and amino acid synthesis. Additionally, plants, algae, and cyanobacteria use carbon dioxide for photosynthesis. The layered composition of the atmosphere minimizes the harmful effects of sunlight, ultraviolet radiation, solar wind, and cosmic rays to protect organisms from genetic damage. The current composition of the atmosphere of the Earth is the product of billions of years of biochemical modification of the paleo atmosphere by living organisms.

The lowest layer of the atmosphere is called troposphere, extending from the planetary surface to the bottom of the stratosphere. The troposphere contains 75 % of the atmosphere mass and is the layer wherein the weather occurs. The height of the troposphere varies between 17 km at the equator and 7.0 km at the poles. The stratosphere extends from the top of the troposphere to the bottom of the mesosphere, representing layer between 15km and 35km of altitude that absorbs most of the ultraviolet radiation that Earth receives from the Sun.

The mesosphere ranges from 50 km to 85 km and is the layer wherein most meteors are incinerated before reaching the surface. From an altitude of 85 km to the base of the exosphere, at 690 km, there is another layer named thermosphere which contains the ionosphere, where solar radiation ionizes the atmosphere. The ionosphere's density is greater at short distances from the planetary surface in the daytime and decreases as the ionosphere rises at night, allowing a greater range of radio frequencies to travel greater distances. Moreover, the Karman line at 100 km is in the thermosphere, which is considered as a theoretical boundary between outer space and the Earth's atmosphere. The exosphere begins at 690 – 1,000 km from the surface and extends to roughly 10,000 km, where it interacts with the magnetosphere of Earth.

Researchers in recent decades have studied the diffusion of microbial cells in the atmosphere. Seetharam et al. (2015, 2016) have found fungal spores belonging to 14 different families on spiderwebs, which are located in the troposphere, whereas the presence of microorganisms in clouds has also been reported (Woo et al., 2018). The evidence of the presence of microorganisms in the upper layers of the atmosphere was found for the first time by using meteorological rockets. Imshenetsky's team found fungal spores as well as bacteria in the mesosphere, at an altitude ranging from 48 - 77 km (Imshenetsky et al., 1978). More recently, some studies reported the presence of bacteria in the stratosphere Shivaji et al. (2006, 2009) (DasSarma et al., 2020) and the viruses (Wickramasinghe et al., 2020). Moreover, bacterial DNA has been even found in the ionosphere, on the illuminator of the international space station (Grebennikova et al., 2018). According to Tesson et al. (2016) Chlorophyta, Bacillariophyta, and Ochrophyta are the most represented taxa, occurring throughout the world, in the lower layers of the atmosphere. Other reviews have described the importance of aerosol microalgae and cyanobacteria and discussed the possible impact of their diffusion on human health and the environment (Tesson et al., 2016; Tesson & Šantl-Temkiv, 2018; Wisniewska et al., 2019).

This brief review gathers the research articles showing the presence of phototrophic microorganisms in the atmosphere, with a special focus on the cyanobacteria and algae at different layers of the atmosphere.

Methods

Air Sampling

Sampling algae from the air is done through passive and active air flow methods. The active air sampling methods use the electric or mechanical pumps to draw the air into/onto the collection device/medium with known rate of airflow. While the passive air sampling methods depends on the natural air movement.

The passive sampling and preliminary investigations are done by exposing Petri dishes containing sterile, solidified, and inorganic nutrient medium known as Bold's Basal Medium , (BBM) or modified Bold 3 N media (B3N) , directly to air for some time (Carson & Brown 1976). By incubating them for some period, this inorganic medium does not encourage the luxurious growth of heterotrophic contaminants (fungi and bacteria) but instead allows only the growth of algae (Sathish et al., 2020; Wiśniewska et al. 2020; Chiu et al., 2020).

The active sampling device, such as the rotarod sampler (Marshall & Chalmers, 1997) relies on the movement of air generated by the moving arms of the sampler. Both arms of the sampler cleaned with acetone, and sterile double adhesive tape is stuck to the arms just before the sampling (Comtois et al., 1999). Rotarod samplers are exposed to air for a short duration (30 min) to minimize the deposition of any toxic substances on the adhesive tapes. The impacted tapes are removed from the arms aseptically, cut into small pieces, and placed face down on Petri plates containing solid BBM to follow the culture-dependent identification method (Sharma et al., 2006; Groot et al., 2021). An impaction culture plate sampler (air IDEAL3P, bioMerieux, France) has also used, which can collect 500 liters of air with a 100 ml/min for 5 min. Air is aspirated in the sampler through a grid perforated with a pattern of 286 calibrated holes. The airstream containing the microbial particles is directed onto the surface of Bold's Basal Medium (BBM) agar (Carson & Brown, 1976) in a sterile petri dish (90mm in diameter) attached to the air sampler (Chu et al., 2013). In the last decades, many other air samplers with similar principles have been developed and used to collect microbes from the air. (Genitsaris et al., 2011; Chu et al., 2013; DeLeon-Rodriguez et al., 2013; Smith, 2018; Aalismail et al., 2021; Wiśniewska et al., 2022).

Identification of algae and cyanobacteria

Identification of airborne algae and cyanobacteria can be done using culture-dependent methods or culture-independent methods. Culture-independent methods are used to identify microbes without cultivating them, while culture-dependent methods require the microbe to be grown after sampling.

Culture-Dependent Method. During the sampling period, airborne particles collected directly onto agar-solidified plates or into a conical flask containing sterile distilled water using passive or active air sampling methods. For the air-drawn plate, we should wait for the growth of the microbe and use microscopy to identify microbes. For the water samples impacted with direct air by the sampler, we can directly add Lugol and can be taken for microscopic analysis. (Carson & Brown, 1976; Sharma et al., 2006; Genitsaris et al., 2011; Chu et al., 2013; Sathish et al., 2020; Wiśniewska et al., 2020, 2022; Chiu et al., 2020).

Culture-Independent Method Air samplers direct the air to specified filters to which the microbes are attached. After recovering the filter, we can extract the DNA and use metagenomic sequencing or amplicon-based sequencing to identify the taxa in the sample (Smith et al., 2018; Dillon et al., 2021; Aalismail et al., 2021; Groot et al., 2021; Drautz-Moses et al., 2022).

An overview of studies reporting Cyanobacteria and algae in the Atmosphere

As mentioned before, the troposphere contains 75 % of the atmosphere's mass. Many studies show the presence of airborne algae and cyanobacteria in the troposphere, either in filaments or in spore forms. The first note of algal presence in the atmosphere dated back to the 1830 Gregory, P. H, (1961). But scientists haven't emphasized the abundance and variety of airborne algae due to the lack of prolonged cultivation after exposure to air. Taxonomically, airborne microalgae belong either to the prokaryote's cyanobacteria (also known as blue-green algae) or some unicellular microeukaryotes. Also, moustaka's team stated that 353 morphological taxa had been observed (Moustaka-Gouni, 2011).

The investigations by VanOvereem (Overeem, 1937) represented their pioneering efforts to recover and cultivate airborne algae. They successfully collected 24 air samples from an airplane at various altitudes over the Netherlands on six different occasions and recovered nine different algal isolates. Among the recovered isolates, *Chlorococcum* appeared most frequently. Samples from an altitude of 500 m provided the most abundant algal flora. Further collections at ground level, using an air pump and rainwater samples, revealed at least eight different species, *Chlorococcum* again being the most abundant. These collection methods also obtained a Myxomycete plasmodium, moss protonemata, and fern prothallia. They also mentioned that the algal content of dust could be extremely high, and the count has revealed no less than 3000 algae per cubic meter. Counts of this nature indicate that algae may exist in sufficient quantity in the air to be a possible cause of inhalant allergy (Brown et al., 1964).

During the summer of 1971 and autumn of 1973, a transect was set up on the island of Hawaii from the coastal city of Hilo up to 6500 ft on the slopes of Mauna Loa. Sterile Petri dishes of agarized BBM were exposed at different altitudes, between 1000 to 5000 ft intervals, for 1 minute each from an automobile traveling at 35 miles per hour. The Plates were incubated for one month on a continuous light cycle of approximately 3500 lux and 19°C, and members belonging to the genera *Chlorella, Chlorococcum, Oocystis*., *Protococcus*. *Hormidium, Calothrix, Oscillatoria, Symploca, Lyngbya, Entiphysalis, Synechocystis, and Monallantus* were observed (Carson & Brown, 1976).

Samples collected 1 meter above the ground between 14 December 1992 and 28 January 1994 at three sites on Signy Island, Antarctica, showed the presence of red cysts (aplanospores), *Chlamydomonas nivalis, Chlorosphaera antarctica*, cyanobacterial filaments, and chlorophyte filaments, probably *Zygnema* spp. (Marshall & Chalmers, 1997).

At the beginning of this century, Sharma et al. (2006) reported that cyanobacteria were the abundant photoautotroph in Varanasi, India, during summer, while winter favors green algae. The presence of diatoms was almost uniform throughout the year. They observed 34 different aero algae genera including *Microcoleus* sp. and *Spirulina* sp. at 2.5 meters in height. They also mentioned the presence of algal particles in the air depending upon the abundance and dynamics of algal source and their release and dispersal in the atmosphere.

Another study is in the city of Thessaloniki, Greece, a densely populated and industrialized city reported to have high ambient concentrations of airborne particles that contain elements such as NaCl, K_2O, NiO, Cr_2O_3, MnO_2, Fe_2O_3, PbO, Cu_2O, ZnO, Sb_4O_6, CdO, and V_2O_5, As_2O_5 and Co_3O_4 at levels greater than the proposed. During the period October 2007 to April 2008, Maria Moustaka-Gouni and her team evaluated the diversity of aero algae in the atmosphere. Twenty-nine species of airborne micro-eukaryotes were identified. Airborne organisms of eight taxa were also detected in the nearby aquatic systems. The algae *Haematococcus lacustris,* a *Chlorella*-like taxon, and *Scenedesmus cf. obliquus,* the heterotrophic nanoflagellates (HNF) *Bodo* sp., *Cafeteria minuta,* and *Rynchomonas nasuta,* and the ciliate *Pattersoniella vitiphila* were present in all three seasons. *Grammatophora* sp., *Nitzschia* sp., *Spumella* sp., *Chlamydomonas* spp., *Chlorosarcinopsis bastropiensis, Gloeotila sp., Lobosphaera tirolensis, Monoraphidium minutum, Mougeotia* sp., *Stichococcus* sp., *Trebouxia impressa, Zygnema* sp. are also found. They also studied the food webs in all seasons. They stated that in all seasons, the abundance ratio of autotrophs to heterotrophs was <1 in the initial phase of the colonization (Week 1), indicating the dominance of heterotrophic microeukaryotes. The <1 ratio was maintained in autumn and winter for 4 weeks. However, in spring, the ratio changed from <1 to >15 through the 6 weeks, suggesting a transition from heterotroph to autotroph dominance (Genitsaris et al., 2011).

A study conducted in Malaysia aimed to investigate the occurrence and distribution of airborne algae and Cyanobacteria (AAC) in various environments, including indoor and outdoor areas of an office building in Kuala Lumpur, between February and October 2008. The results showed that AAC were present in almost every place, with Cyanobacteria, Chlorophyta, and Bacillariophyta being the most common taxa identified, some of them including *Chlamydomonas* sp., *Chlorococcum humicola* (Nägeli) Rabenhorst, *Chlorella ellipsoidea* Gerneck, *Scenedesmus bijugus* (Turp.) Lagerheim, *Phormidium retzii* (Agardh) Gomont, *Pseudanabaena* sp., and an unidentified filamentous cyanobacterium. The study also found that areas with heavy human movement had a high occurrence of AAC, with the highest occurrence (75%) recorded in the surrounding areas of the building and the lowest (45%) on the lower ground floor, an area exposed to the outdoor environment. In addition, some AACs were also detected in wall scraping and soil samples. The findings suggest that human movement is an important factor affecting the dispersal of AAC, which has implications for public health and indoor air quality (Chu et al., 2013).

To address airborne microorganisms in the upper troposphere and lower stratosphere, Smith and team collected samples from altitudes in the lower stratosphere (about 12 km) using flight-validated a novel Aircraft Bioaerosol Collector (ABC) which was installed on NASA's C-20A, and on four consecutive missions flown over the United States (US) from 30 October to 2 November 2017. Bioaerosols were captured on DNA-treated gelatinous filters inside a cascade air sampler, then analyzed with molecular and culture-based characterization which summarized the eight most abundant phyla detected in the study including Cyanobacteria (Smith et al., 2018).

In 2016 and 2017, Tesson and Šantl-Temkiv (2018) investigated for ice nucleation active (INA) compounds in Sweden. They isolated 81 strains of airborne microalgae from snow samples and determined their taxonomy by sequencing their ITS markers, 18S rRNA genes, or 23S rRNA genes. Out of the 81 isolated airborne strains, 56.8% were affiliated with Chlorophyta. The majority of these strains were represented by the class Trebouxiophyceae (40 out of 46 strains), while the rest were affiliated with Chlorophyceae (6 out of 46 strains) (Tesson & Šantl-Temkiv 2018).

We know that viable microalgae occur in the air. In 2013, to study whether microalgae can survive the stresses such as UV, desiccation, and freezing temperatures at high altitudes during a long-distance dispersal Chia–Sheng Chiu and team isolated four freshwater airborne green microalgae from Dongsha Atoll in South China Sea at two meters above the ground and identified as *Scenedesmus sp. DSA1, Coelastrella sp. DSA2, Coelastrella sp. DSA3* and *Desmodesmus sp.* Chlorophyta was found to be abundant in their samples (Chiu et al., 2020).

The Adriatic Sea region is one of the economically important water bodies due to tourism. To get information on the taxonomic composition of cyanobacteria and microalgae, The first sampling in this area conducted by K. A. Wiśniewska et al. (2020) between 11th and 15th June 2017. The study revealed the presence of cyanobacteria and microalgae, as well as the cyanobacterium *Snowella sp.* And the green alga *Tetrastrum sp.,* taxa that had not been previously documented in the atmosphere in any other studies. This sampling was carried out in the northern part of Italy (station 1), one in Croatia (station 2), and two in Montenegro (station 3 and station 4), which is 50 meters from the seashore and 1 meter above the ground.

To study the diversity of airborne algae in Bangalore, India, air samples were collected in four sites using the Petri plate exposure method and Benecks agar medium. A total of fifteen airborne algae belonging to twelve genera were identified, including members of Cyanobacteria, Chlorophyceae, and Bacillariophyceae. Cyanobacteria were dominant group with a total of seven genera identified: *Oscillatoria, Lyngbya, Microcoleus, Chroococcus, Nostoc, Anabaena, Hapalosiphon, Gloeocapsa,* and *Myxosarcina*. The Bacillariophycean members identified were *Cymbella and Nitzschia*, and the genus *Chlorella* represented the *Chlorophyceae*. Most of the species present in air samples were soil algae (Sathish et al., 2020).

Another study has investigated airborne eukaryotic communities (AEC) in dust of the highest dust flux place on the planet, the west coast of North Africa and Central Asia. Samples of atmospheric dust were collected from onshore and offshore locations of the Red Sea at ~7.5 meters over the sea level in Thuwal, Saudi Arabia, over 14 months (fall 2015–fall 2016). Algae from Rhodophyta, Chlorophyta, and Bacillariophyta were identified using Miseq sequencing. As usual, Chlorophyta was particularly abundant (0.97%) (Aalismail et al., 2021).

From March to June 2019, were collected 16 fan dust samples from 8 residences to investigate the intramural diversity of airborne algae in Pune, India over ten days. A total (of 108) aero-algal forms were recorded. Out of which 107 were Cyanophyta, and only one was *Chlorophyta*. *Anabaena, Scytonema, Calothrix,* and *Scenedesmus* were among the allergic aero-algal genera (Kamble & Pandkar 2021).

Recently, a study has been conducted to investigate the dispersal patterns of microbial taxa in the vertical air column. they collected samples from a meteorological tower in Germany and a flight at a height of 3500 meters, using dry electret filters and SASS3100 air samplers operated at an airflow rate of 300 L/min. Metagenomic Sequencing was performed to analyze the taxonomic composition of the airborne microbial communities, which showed differences in composition patterns based on the time of day and height above ground. the results revealed the presence of cyanobacteria and chloroflexi along with other prokaryotes and eukaryotes. The study also, showed that DNA amounts varied with time of day and height, highlighting the importance of investigating height-related changes in a time-specific manner. Specifically, the study observed a 400% difference in DNA abundance between day and night samples (Drautz-Moses et al., 2022).

Wiśniewska et al. (2022) recently have presented an innovative investigation of the washout efficiency of airborne cyanobacteria and microalgae in the Gulf of Gdańsk (southern Baltic Sea). Sampling was carried out in 2019 at 20 meters above sea level, which showed that the number of microalgae and cyanobacteria cells decreased by up to 87% after a rainfall event compared to before the rainfall event. Several harmful taxa, including

Chlorococcum sp., Oocystis sp., *Anabaena* sp., *Leptolyngbya* sp., *Nodularia* sp., *Pseudanabaena* sp., *Synechococcus* sp., *Synechocystis* sp., and *Gymnodinium* sp., were washed out by rain. This is crucial for human health as it reduces the chance of people inhaling these species and their toxic metabolic products. Figure 1 supports the washout of the biomass and aerosols due to rain and reveals the mountains in the background. The images were captured on two different dates in February 2023, before and after a rainfall event.

Sylvie Tesson and her team (2016) summarises the diversity of airborne microalgae. The review discusses their emission, transportation, deposition, and adaptation to atmospheric stress, as well as the consequences of their dispersal on health and the environment. It also includes a discussion of state-of-the-art techniques for detecting and modelling airborne microalga dispersal. Additionally, Hallmann (2015) and Tesson et al. (2016) investigated the algal colonization on different materials (building

Figure 1: Chiang Mai, Thailand. Top: photo taken on 15/02/2023. Bottom: photo taken on 17/02/2023, after a rainfall.

walls, marble monuments, surfaces in urban environments) exposed to airborne algae.

Lederberg (1960) first used the term "exobiology" to describe the exploration of life at higher elevations, from the stratosphere into the space field realm. The presence of bacteria, archaea and fungi in the upper troposphere has been reported by Rodriguez et al. (2013). Furthermore, fungi seem to play an important role on epidemiology and climate change by cloud condensation or nucleation (DasSarma et al., 2020). Some bacterial and fungal spores have also been found in the mesosphere and thermosphere, whereas the presence of microalgae in troposphere has been scarcely studied and the unequivocal evidence for algae in the stratosphere and other upper layers has not been found. The study by Zerveas et al. (2021) showed the ability of microalgae to turn hostile atmospheres into O2-rich atmospheres. These primary producers can start a chain of life and can maintain it, as also proposed by Macário et al. (2022), who mentioned cyanobacteria as candidates to support Mars colonization. I strongly believe that an unexplored ecosystem exists in the stratosphere, starting with these primary producers, which might play a relevant role in the earth's environment and changing climate.

Concluding remarks

The atmosphere is considered one of the most extreme environments due to its low nutrient levels, extreme temperatures, and high radiation levels. It is a difficult place to mimic and study, and sampling techniques need to be advanced. In this mini review, we discussed the studied algal diversity in the troposphere and its role, which is supported by valid evidence. However, to fully understand the importance of these primary producers in global climate change and biomass distribution, we need to study all the layers of the atmosphere. In the past few decades, scientists have shown that microbes are ubiquitous, found from the top ionosphere to the deep trenches, and involved in all cycles, such as carbon, nitrogen, and oxygen. This indicates their crucial role in climate change. Nevertheless, there is still much to learn about many microbes and their roles in different ecosystems. Currently, only 0.0001% of microbial diversity is known to humankind. Therefore, exploring microbial diversity in the atmosphere is necessary to understand the exact picture of microbial ecology and its role in climate change.

Acknowledgments

I would thank Petr Kolar for the images.

References

Aalismail N. A., Díaz-Rúa R., Geraldi N., Cusack M., Duarte C. M. (2021). Diversity and Sources of Airborne Eukaryotic Communities (AEC) in the Global Dust Belt over the Red Sea. *Earth Syst. Environ.*, **5(2)**, 459–471. https://doi.org/10.1007/s41748-021-00219-4

Brown R. M., Larson D. A., Bold H. C. (1964). Airborne Algae: Their Abundance and Heterogeneity. *Science*, **143(3606)**, 583–585. https://doi.org/10.1126/science.143.3606.583

Carson J. L., Brown R. M. J. (1976). the Correlation of Soil Algae Airborne Algae and Fern Spores With Meteorological Conditions on the Island of Hawaii Usa. *Pacific Science*, **30(2)**, 197–205.

Chiu C. S., Chiu P. H., Yong T. C., Tsai H. P., Soong K., Huang H. E., Chen C. N. N. (2020). Mechanisms protect airborne green microalgae during long distance dispersal. *Sci. Rep.* **10(1**), 1–12. https://doi.org/10.1038/s41598-020-71004-y

Chu W. L., Tneh S. Y., Ambu S. (2013). A survey of airborne algae and cyanobacteria within the indoor environment of an office building in Kuala Lumpur, Malaysia. *Grana*, **52(3)**, 207–220. https://doi.org/10.1080/00173134.2013.789925

Comtois P., Alcazar P., Néron D. (1999). Pollen counts statistics and its relevance to precision. *Aerobiologia* **15(1)**, 19–28. https://doi.org/10.1023/A:1007501017470

DasSarma P., Antunes A., Simões M. F., DasSarma S. (2020). Earth's Stratosphere and Microbial Life. *Curr Issues Mol Biol* **38**, 197–244. https://doi.org/10.21775/cimb.038.197

DeLeon-Rodriguez N., Lathem T. L., Rodriguez-R L. M., Barazesh J. M., Anderson B. E., Beyersdorf A. J., Ziemba L. D., Bergin M., Nenes A., Konstantinidis K. T. (2013). Microbiome of the upper troposphere: Species composition and prevalence, effects of tropical storms, and atmospheric implications. *Proc. Natl. Acad. Sci.* **110(7)**, 2575–2580. https://doi.org/10.1073/pnas.1212089110

Dillon K. P., Correa F., Judon C., Sancelme M. (2021). *Cyanobacteria and Algae in Clouds and Rain in the Area of. 87*(1), 1–15.

Drautz-Moses D. I., Luhung I., Gusareva E. S., Kee C., Gaultier N. E., Premkrishnan B. N. V., Lee C. F., Leong S. T., Park C., Yap Z. H., Heinle C. E., Lau K. J. X., Purbojati R. W., Lim S. B. Y., Lim Y. H., Kutmutia S. K., Aung N. W., Oliveira E. L., Ng S. G., … Schuster S. C. (2022). Vertical stratification of the air microbiome in the lower troposphere. *Proc. Natl. Acad. Sci.* **119(7)**, 1-8. https://doi.org/10.1073/pnas.2117293119

Genitsaris S., Moustaka-Gouni M., Kormas K. A. (2011). Airborne microeukaryote colonists in experimental water containers: Diversity, succession, life histories and established food webs. *Aquat. Microb. Ecol.* **62(2)**, 139–152. https://doi.org/10.3354/ame01463

Grebennikova T. V., Syroeshkin A. V., Shubralova E. V., Eliseeva O. V., Kostina L. V., Kulikova N. Y., Latyshev O. E., Morozova M. A., Yuzhakov A. G., Zlatskiy I. A., Chichaeva M. A., Tsygankov O. S. (2018). The DNA of Bacteria of the World Ocean and the Earth in Cosmic Dust at the International Space Station. *Sci. World J.* **2018**, 1-8. https://doi.org/10.1155/2018/7360147

Gregory P. H. (1961). The microbiology of the atmosphere.*The microbiology of the atmosphere*.

Groot G. A. De, Geisen S., Wubs E. R. J., Meulenbroek L., Laros I., Snoek L. B., Lammertsma D. R., Hansen L. H., Slim P. A. (2021). The aerobiome uncovered: Multi-marker metabarcoding reveals potential drivers of turn-over in the full microbial community in the air. *Environ. Int.* **154**, 106551. https://doi.org/10.1016/j.envint.2021.106551

Hallmann C. (2015). Biodiversity of terrestrial algal communities from soil and air-exposed substrates using a molecular approach Aeroterrestrial algae Aeroterrestrial algae. *PhD Thesis, Göttingen, Germany*.

Imshenetsky A. A., Lysenko S. V., Kazakov G. A. (1978). Upper boundary of the biosphere. *Appl. Environ. Microbiol.* **35(1)**, 1-5. https://doi.org/10.1128/aem.35.1.1-5.1978

Kamble A. K., Pandkar J. T. (2021). Enlisting Aero-algal Flora and Algal Allergens Using Fan Dust Sampling Method from Pune, Maharashtra. *Biosci. Biotech. Res. Asia*, **18(4)**, 767–778. https://doi.org/10.13005/bbra/2958

Lederberg J. (1960). Exobiology: Approaches to life beyond the earth. *Science* **132**(3424), 393–400. https://doi.org/10.1126/science.132.3424.393

Macário I. P. E., Veloso T., Frankenbach S., Serôdio J., Passos H., Sousa C., Gonçalves F. J. M., Ventura S. P. M., Pereira J. L. (2022). Cyanobacteria as Candidates to Support Mars Colonization: Growth and Biofertilization Potential Using Mars Regolith as a Resource. *Front. Microbiol.* **13**, 1–14. https://doi.org/10.3389/fmicb.2022.840098

Marshall W. A., Chalmers M. O. (1997). Airborne dispersal of antarctic terrestrial algae and cyanobacteria. *Ecography* 20(6), 585–594. https://doi.org/10.1111/j.1600-0587.1997.tb00427.x

Moustaka-Gouni M. (2011). Airborne Algae and Cyanobacteria Occurrence and Related Health Effects. *Front. Biosci.* **E3(2)**, 285. https://doi.org/10.2741/e285

Mus F., Crook M. B., Garcia K., Costas A. G., Geddes B. A., Kouri E. D., Paramasivan P., Ryu M. H., Oldroyd G. E. D., Poole P. S., Udvardi M. K., Voigt C. A., Ané J. M., Peters J. W. (2016). Symbiotic nitrogen fixation and the challenges to its extension to nonlegumes. *Appl. Environ. Microbiol.* **82(13)**, 3698–3710. https://doi.org/10.1128/AEM.01055-16

Nichols H. W., Bold H. C. (1965). Trichosarcina polymorpha Gen. et Sp. Nov. . *Phycol.* **1(1)**, 34–38. https://doi.org/10.1111/j.1529-8817.1965.tb04552.x

Overeem M. van. (1937). by (from Leyden). (With Description Absorbing Mounting Sampling flights Comparison pheric of results , Microbiological atmosphere point study general biological allergic phenomena The Leyden Botanical Laboratory chiefly living (in sense) organisms , *Recueil Des Travaux Botaniques Néerlandais*, *34*(1), 388–442. https://natuurtijdschriften.nl/pub/552615

Sathish C., Rekha, C. R. Sahana, C., Shruthi S. (2020). *A Qualitative Investigation of Airborne Algae in Government Science College Campus Bengaluru , India*. **7(5**), 24–28. *https://doi.org/https://doi.org/10.26438/ijsrbs/v7i5.2428*

Seetharam D. S., Ramakrishna H., Prabhakar R., Kailash J. G. (2016). *Aerobiologic Al Stud Y From the Spider Web S of P Study Webs Pakhal Wildlife Sanctu Ar Y , W Arang Al District , Telang Arangal District , St Sta*. **11(2**), 851–856.

Sharma N.,K. Rai A., Singh S. (2006). Meteorological factors affecting the diversity of airborne algae in an urban atmosphere. *Ecography* **29(5)**, 766–772. https://doi.org/10.1111/j.2006.0906-7590.04554.x

Shivaji S., Chaturvedi P., Begum Z., Pindi P. K., Manorama R., Padmanaban D. A., Shouche Y. S., Pawar S., Vaishampayan P., Dutt C. B. S., Datta G. N., Manchanda R. K., Rao U. R., Bhargava P. M., Narlikar J. V. (2009). Janibacter hoylei sp. nov., Bacillus isronensis sp. nov. and Bacillus aryabhattai sp. nov., isolated from cryotubes used for collecting air from the upper atmosphere. *Int. J. Syst. Evol. Microbiol.* **59(12)**, 2977–2986. https://doi.org/10.1099/ijs.0.002527-0

Shivaji S., Chaturvedi P., Suresh K., Reddy G. S. N., Dutt C. B. S., Wainwright M., Narlikar J. V., Bhargava P. M. (2006). Bacillus aerius sp. nov., Bacillus aerophilus sp. nov., Bacillus stratosphericus sp. nov. and Bacillus altitudinis sp. nov., isolated from cryogenic tubes used for collecting air samples from high altitudes. *Int. J. Syst. Evol. Microbiol.* **56(7)**, 1465–1473. https://doi.org/10.1099/ijs.0.64029-0

Smith D. J., Ravichandar J. D., Jain S., Griffin D. W., Yu H., Tan Q., Thissen J., Lusby T., Nicoll P., Shedler S., Martinez P., Osorio A., Lechniak J., Choi S., Sabino K., Iverson K., Chan L., Jaing C., McGrath J. (2018). Airborne bacteria in earth's lower stratosphere resemble taxa detected in the troposphere: Results from a new NASA Aircraft Bioaerosol Collector (ABC). *Front. Microbiol.* **9,** 1752. https://doi.org/10.3389/fmicb.2018.01752

Tesson S. V. M., Šantl-Temkiv T. (2018). Ice nucleation activity and aeolian dispersal success in airborne and aquatic microalgae. *Front. Microbiol.* ***9**,* 2681. https://doi.org/10.3389/fmicb.2018.02681

Tesson S. V. M., Skjøth C. A., Šantl-Temkiv T., Löndahl J. (2016). Airborne Microalgae: Insights, Opportunities, and Challenges. *Appl. Environ. Microbiol.* **82(7)**, 1978–1991. https://doi.org/10.1128/AEM.03333-15

Wickramasinghe N. C., Maganarachchi D., Temple R., Wallis D. H., Steele E. J., Vithanage M., Gorczynski R. M., Tokoro G., Klyce B., Slijepcevic P. (2020). The Search for Bacteria and Viruses in the Stratosphere. *Adv. Astrophys.* **5(2)**. https://doi.org/10.22606/adap.2020.52003

Wiśniewska K., Lewandowska A. U., Śliwińska-Wilczewska S. (2019). The importance of cyanobacteria and microalgae present in aerosols to human health and the environment – Review study. *Environ. Int.*, **131**(2019), 104964. https://doi.org/10.1016/j.envint.2019.104964

Wiśniewska K. A., Śliwińska-Wilczewska S., Lewandowska A. U. (2020). The first characterization of airborne cyanobacteria and microalgae in the Adriatic Sea region. *PLoS ONE*, **15(9)**, e0238808 https://doi.org/10.1371/journal.pone.0238808

Wiśniewska K. A., Śliwińska-Wilczewska S., Lewandowska A. U. (2022). Airborne microalgal and cyanobacterial diversity and composition during rain events in the southern Baltic Sea region. *Sci. Rep.***12(1)**, 1-9. https://doi.org/10.1038/s41598-022-06107-9

Woo C., An C., Xu S., Yi S. M., Yamamoto N. (2018). Taxonomic diversity of fungi deposited from the atmosphere. *ISME J.* **12(8)**, 2051–2060. https://doi.org/10.1038/s41396-018-0160-7

Zerveas S., Kydonakis E., Moutidis P., Maragkoudakis A., Kotzabasis K. (2021). Microalgae strategy in anoxic atmospheres with various CO2 concentrations – Environmental and (astro)biotechnological perspectives. *Environ. Exp. Bot.*, **187**(December 2020), 104474. https://doi.org/10.1016/j.envexpbot.2021.104474

Bulletin of Regional Natural History (BORNH) ISSN 2724-4393.