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Bioaerosol emissions from open microalgal processes and their potential environmental impacts: what can be learned from natural and anthropogenic aquatic environments?

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Open processes for microalgae mass cultivation and/or wastewater treatment present an air–water interface. Similarly to other open air-aquatic environments, they are subject to contamination, but as such, they also represent a source of bioaerosols. Indeed, meteorological, physico-chemical and biological factors cause aerial dispersion of the planktonic community. Operating conditions like liquid mixing or gas injection tend to both enhance microbial activity, as well as intensify aerosolization. Bacteria, virus particles, fungi and protozoa, in addition to microalgae, are all transient or permanent members of the planktonic community and can thus be emitted as aerosols. If they should remain viable, subsequent deposition on various habitats could instigate their colonization of other environments and the potential expression of their ecological function.

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Introduction

The presence and activity of microorganisms in the atmosphere have been known and described since the middle of the nineteenth century [1••]. The strong interactions between the Earth's surface and the lowest layer of the atmosphere lead to aerial dispersion and transport of gas, particles and biological material. Natural, agricultural and urban environments produce bioaerosols [1••,2]. They are composed of bacteria, reproductive plant cells (pollen), fungi and protozoa (cysts), in the form of single cells or aggregates and also fragments of diverse biological materials [1••,3]. They vary in terms of diversity and concentration depending on the source of emission, the release and transport conditions and the season [1••,4,5]. As a consequence, aerial dispersion of microorganisms contributes to the colonization of various environments [1••,6,7], spreading of diseases [8,9]. They can also have an impact on the climate [10].

Materials are exchanged at the interface between the atmosphere and open waters (such as seas, oceans, coastal regions, rivers and lakes). Furthermore, the physical disturbance of the interface impacts these exchanges qualitatively and quantitatively [11]. Algal ponds dedicated to microalgae mass cultivation and/or wastewater treatment are open-air aquatic systems. They are thus confronted to these same phenomena. Microalgae cultivation can be performed within either open or closed processes. Open processes present many advantages such as low-cost mass cultivation and wastewater treatment. They are known to be sensitive to airborne contaminations [12••] due to aerial transport or other vectors [4]. Indeed, the intrinsic nature of these processes makes them particularly exposed to their physical and biological environments. It can therefore be assumed that bioaerosols emitted from open microalgal processes would follow the same physical rules as any bioaerosol from any air–water interface.

The study of the production and impacts of bioaerosols is a highly complex and multidisciplinary topic. The purpose of this paper is to provide an overview of the potential microorganism emissions from open air microalgal processes and their potential environmental impacts. Considering the two main functions associated to open ponds — microalgae cultivation for specific high value molecules or biofuel production and wastewater treatment — this survey focuses in particular on microorganisms (microalgae but also bacteria, viruses, fungi and protozoa) which are potentially emitted from open algal processes and that can affect the latter. The physical mechanisms linked to dispersion as well as their potential consequences are also discussed.

Aerosolization principles

Bioaerosol generation and dispersion from the air–water interface involve complex mechanisms for which many variables interact [11]. The physical and biological integrity of open microalgal processes are impacted by both meteorological conditions and mechanical forces resulting from specific pond operating conditions. Bioaerosol generation in shallow lagoons and algal ponds is mainly related to meteorological conditions. However it is also enhanced by high rate operating conditions (e.g., optimization of liquid mixing and gas–liquid transfer) in advanced open algal processes.

Particles released from a surface result from external forces which become stronger than the bonding forces. Bubble bursting is considered to be the major generator of aerosols [2,8,13,14•]. Löndahl [8] reported three types of bioaerosol production in open waters: spume drops issued from breaking waves, film drops and jet props originating from bubbles. In addition, the quantity of biological material carried by bubbles and then released by their disruption can increase by several orders of magnitude [2]. Aerial release can arise from scum and foam formation at the water surface and during their subsequent total or partial disintegration [4].

Meteorological conditions (wind, rain, temperature and humidity) directly affect the release, dispersion and activity of bioaerosols [2,5,9]. Wind strength, direction and velocity contribute to this phenomenon, through wave formation via spume production or direct dispersion of water, film and jet drops and foams [4,5]. Rainfall can act as a contamination vector (as described below), as it leads to the dispersal of microorganisms when raindrops impact the water surface. Other meteorological factors such as temperature and humidity will have an effect on the time spent in the atmosphere before deposition as well as on the survival of aerosolized microorganisms. It is also worth mentioning that the concentration of microorganisms in the atmosphere can significantly rise due to seasonal, exceptional or episodic meteorological events such as storms and heavy rainfall.

Advanced open processes such as High Rate Algal Ponds (HRAP) [12••], unlike simple ponds, can undergo physical improvements (e.g., optimized channel geometry, liquid mixing, CO_2 addition and low water depth) for enhancing the biological activity. Pond mixing ensures optimal diffusion of the input flow (wastewater nutrients), maintains the cells in suspension in the culture, improves light accessibility and prevents thermal stratification. Similarly, the mechanical action of mixing devices (paddlewheels, water jets, propellers, Archimedes screws and airlifts [12••]) contributes to increasing bubble rising. In the case of paddlewheels, a direct aerial dispersion can occur when the paddles are above the water level, the wind significantly contributing to boost this dispersion. In order to enhance photosynthetic activity, the microalgae in the pond can be fed with inorganic carbon in the form of CO_2 [12••,15]. Pure CO_2 or CO_2 produced by industrial gas waste emissions is transferred to the liquid phase with injectors and via the generation of microbubbles. For uncovered injection devices, generated bubbles would reach the air–water interface.

Besides meteorological and process variables, the structure of the planktonic microbial community can influence the quality and quantity of emitted bioaerosols. Indeed, species, size, shape, cellular organization and particle adhesion (dust, salts or organic matrixes) can lead to a differential aerial dispersion of the pond community.

Aquatic atmosphere microbiology

In open processes for microalgal mass cultivation or wastewater treatment, the microbial community presents a large diversity. As symbionts, pathogens or predators, bacteria, viruses and ciliates are part of the planktonic ecosystem structure [16•,17,18] and can be transiently or permanently present. Their presence depends on the feeding strategy, the design of the process, the geographical location and the season. However, bioaerosols released from open microalgal processes are still poorly documented in today's scientific literature. Furthermore, their potential impacts can only be assessed by extrapolating the mechanisms described in natural aquatic environments.

As seen above, the disturbance of the surface water microlayer results in the formation of bioaerosol. The surface water microlayer can be modeled as a gelatinous film and constitutes a microbial habitat at the air–water interface where compounds and particles can concentrate [18]. Enrichment in microorganisms and other materials occurs firstly in the surface microlayer and secondly in the aerosol [13,14•,19]. Actually, a positive correlation has already been described between the concentration in biological material in the water and the concentration in emitted aerosols [13,19,20], pointing to an enrichment in the biological content of the aerosol. Hence, additional data are required so as to better monitor the emission flux of aerosols, although technical sampling issues still prevent successful flux measurements [21] (see Box 1).

The particle-size distribution of aerosols and the environmental conditions both have an influence on the persistence and seasonal variations in emission rates as well as on the types of emitted microbial species. These factors affect the dispersal of bioaerosols and the impacts of aerial contaminations of open pond [22–24]). In coastal sites, available data report that airborne microbes are primarily found in particles larger than the size of an individual cell, suggesting that they could be rafted on residues from water spray (gel-like particles of the surface microlayer, debris, etc.) or attached to other microorganisms [13,25].

Viruses can infect planktonic microorganisms such as bacteria, cyanobacteria and eukaryotic algae and can significantly reduce algal population in a culture within