A new look at the last decade of research on the rise of harmful airborne cyanobactezria and microalgae and its broad consequences

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**Abstract**

Human-induced environmental changes can synergistically promote the spread and growth of potentially harmful cyanobacteria and microalgae in the atmosphere. On the other hand, we should not forget the role of these microorganisms on the climate change. This is all the more important because our decade-long research has shown the year-round presence of cyanobacteria and microalgae in the atmosphere. The present study identifies the relationships between processes occurring in the sea, the primary source of cyanobacteria and microalgae, and their presence in the atmosphere. Furthermore, this review highlights which scientific techniques, known from studies on other bioaerosols, are worth applying in the research on airborne cyanobacteria and microalgae. We also present the future prospects of the studies in the context of advancing machine learning techniques. Moreover, we identify the most favorable and unfavorable time of the year for human exposure to cyanobacteria and microalgae. We prove that cyanobacteria and microalgae are dominant in the air in the summer months, when tourism is actively developing. We also examine the impact of inhaling airborne cyanobacteria and microalgae on human health, not only as potential allergens but also as organisms capable of transferring harmful toxins. This study summarizes research conducted over the past ten years in the Baltic Sea region with new unpublished data as well as incorporates the latest global research trends in Central Europe.

**Introduction**

Bioaerosols are a diverse group of microorganisms and their fragments released into the atmosphere from aquatic and terrestrial environments. This group includes bacteria, viruses, fungi, pollen, cyanobacteria, and microalgae (Urbano et al., 2010; Després et al., 2012; Genitsaris et al., 2011; Wiśniewska et al., 2019). Despite growing interest in airborne cyanobacteria, microalgae, and their associated toxins, most aerobiological research continues to focus on pollen, bacteria, and fungi. As a result, airborne cyanobacteria and microalgae remain among the least understood groups in aerobiology (Després et al., 2012; Wiśniewska et al., 2019).

Recently, the concept of air eutrophication has gained attention, highlighting the link between anthropogenic activities, water eutrophication, and air quality (Sun et al., 2023). This framework underscores how human-induced environmental changes—including water excessive nutrient enrichment, global warming, air pollution, and artificial light at night—can collectively promote the spread and proliferation of airborne cyanobacteria and microalgae. Beyond ecological consequences, air eutrophication may pose risks to human health through inhalation of airborne toxins such as microcystin-LR (MC-LR), emphasizing the need for urgent interdisciplinary research to understand its mechanisms and impacts.

Research on atmospheric cyanobacteria and microalgae typically begins with identifying their taxonomic composition. Studies in this field can be broadly categorized into those that focus on taxonomic identification and relative proportions of these microorganisms and those that quantify their abundance (El-Gamal et al., 2008; Lewandowska et al., 2017; Wiśniewska et al., 2020). Identifying the taxonomic composition is crucial for assessing potential health risks associated with these organisms (Genitsaris et al., 2011; Wiśniewska et al., 2019). Additionally, some studies explore the environmental factors influencing their presence (Carson & Brown, 1976; Sharma et al., 2006; Rosas et al., 1989a; Wiśniewska et al., 2022). However, further investigation is needed to fully understand the health and environmental impacts of airborne cyanobacteria and microalgae.

One of the main challenges in this field is accurately quantifying cyanobacteria and microalgae in the atmosphere due to limitations in research techniques and the absence of standardized methodologies (Wiśniewska et al., 2019). Guiry et al. (2012) suggested that the number of identified airborne taxa is significantly underestimated, with many species yet to be described. Moreover, some regions remain unexplored in this context (Wiśniewska et al., 2019). Since the publication of Wiśniewska et al. (2019), research in this field has expanded considerably, with new studies emerging from e.g. France (Dillon et al., 2020), Slovakia (Žilka et al., 2023), and Canada (Dales et al., 2025).

This study aims to address three key issues. First, it examines the relationship between climate change, particularly global warming over the past decade, and the year-round presence of cyanobacteria and microalgae in the atmosphere. Second, it investigates the meteorological factors influencing airborne cyanobacteria and microalgae in the Baltic Sea region, along with their physiological characteristics and possible adaptations. This analysis identifies periods of heightened and reduced human exposure risk in the area of ​​eutrophicated water reservoirs. Third, it explores the potential health impacts of inhaling airborne cyanobacteria and microalgae, expanding beyond their role as potential allergens to their capacity for transferring harmful toxins and other substances into the human body. Finally, the study outlines future research directions, including the potential application of machine learning to better understand the ecological significance of airborne cyanobacteria and microalgae and their effects on human health and climate.

**Results**

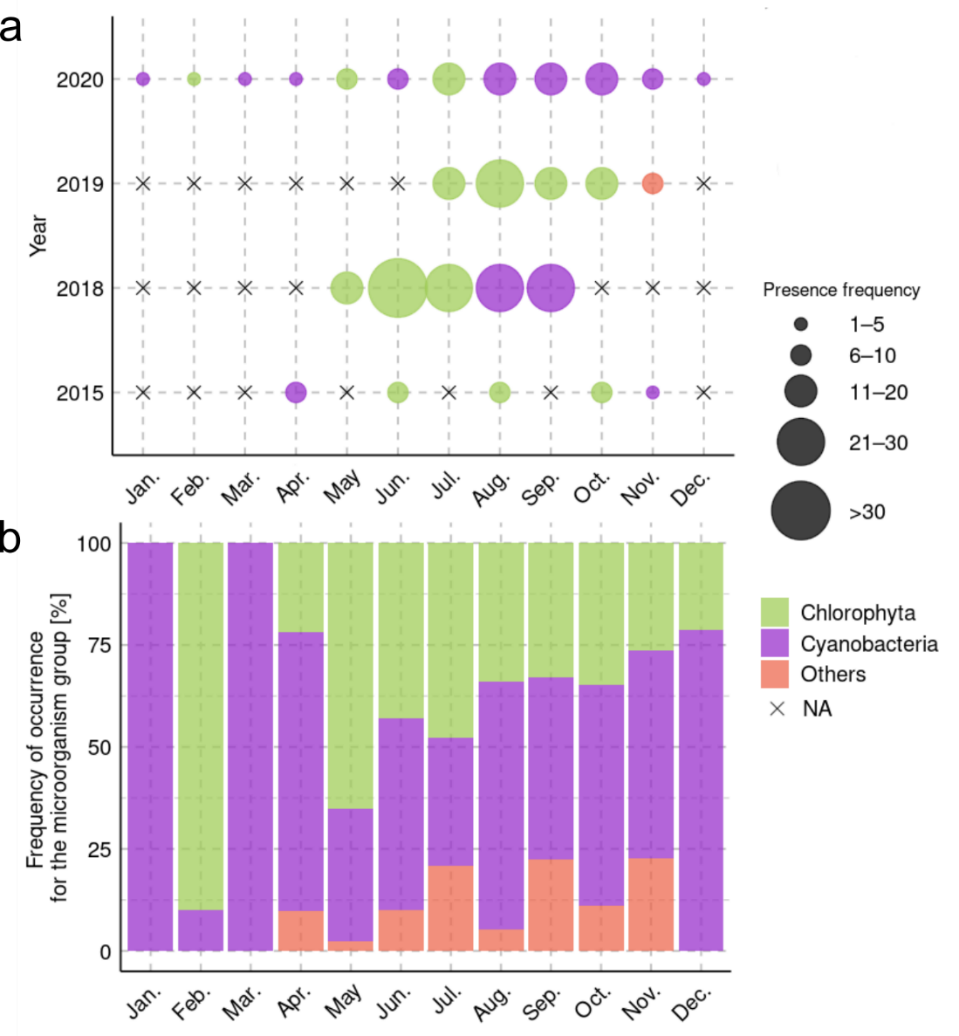
**Global Warming and the Year-Round Presence of Cyanobacteria and Microalgae in the Air**

The rise in air temperature is a well-documented scientific phenomenon observed on both regional and global scales (Hansen et al., 2000; Neumann et al., 2012; Kahru et al., 2016). In the Baltic Sea region, temperature increases have been particularly pronounced, surpassing the global average. For example, in Poland (Central Europe), the mean air temperature has risen by 0.28°C per decade over the past 71 years, amounting to an overall increase of approximately 2°C (Marosz et al., 2023). Similar trends have been recorded across the Baltic region since the late 19th century, with annual mean temperatures rising faster (0.08°C) than the global average (0.05°C) (HELCOM, 2021). The increase is accompanied by large multidecadal variations, in particular during winter, but the warming is seen for all seasons and is largest during spring. These climate change have already led to significant environmental shifts, such as reduced ice cover duration and an extended phytoplankton growing season, which has more than doubled in the Baltic Proper—from 110 days in 1998 to 220 days in 2013 while excluding the shallow coastal areas and up to 284 days between 2014 and 2017 including shallow waters (Kahru et al., 2016; Wasmund et al., 2019).

Warmer conditions, coupled with anthropogenic nutrient loading, have intensified phytoplankton blooms in the Baltic Sea (Łysiak-Pastuszak et al., 2004; Neumann et al., 2012; Ahola et al., 2021), highlighting the direct link between climate change and nutrient-driven ecosystem imbalances. While the Baltic Sea provides a regional case study, eutrophication is a global issue affecting coastal and inland waters worldwide. Recent global assessments using satellite-derived chlorophyll-*a* measurements have identified over 1 million km² of coastal waters exhibiting potential eutrophic conditions, with deteriorating trends far outweighing those showing signs of recovery (de Raús Maúre et al., 2021). Both water eutrophication and rising air temperatures contribute to the concept of air eutrophication, a process that facilitates the presence and spread of cyanobacteria and microalgae in the atmosphere (Sun et al., 2023).

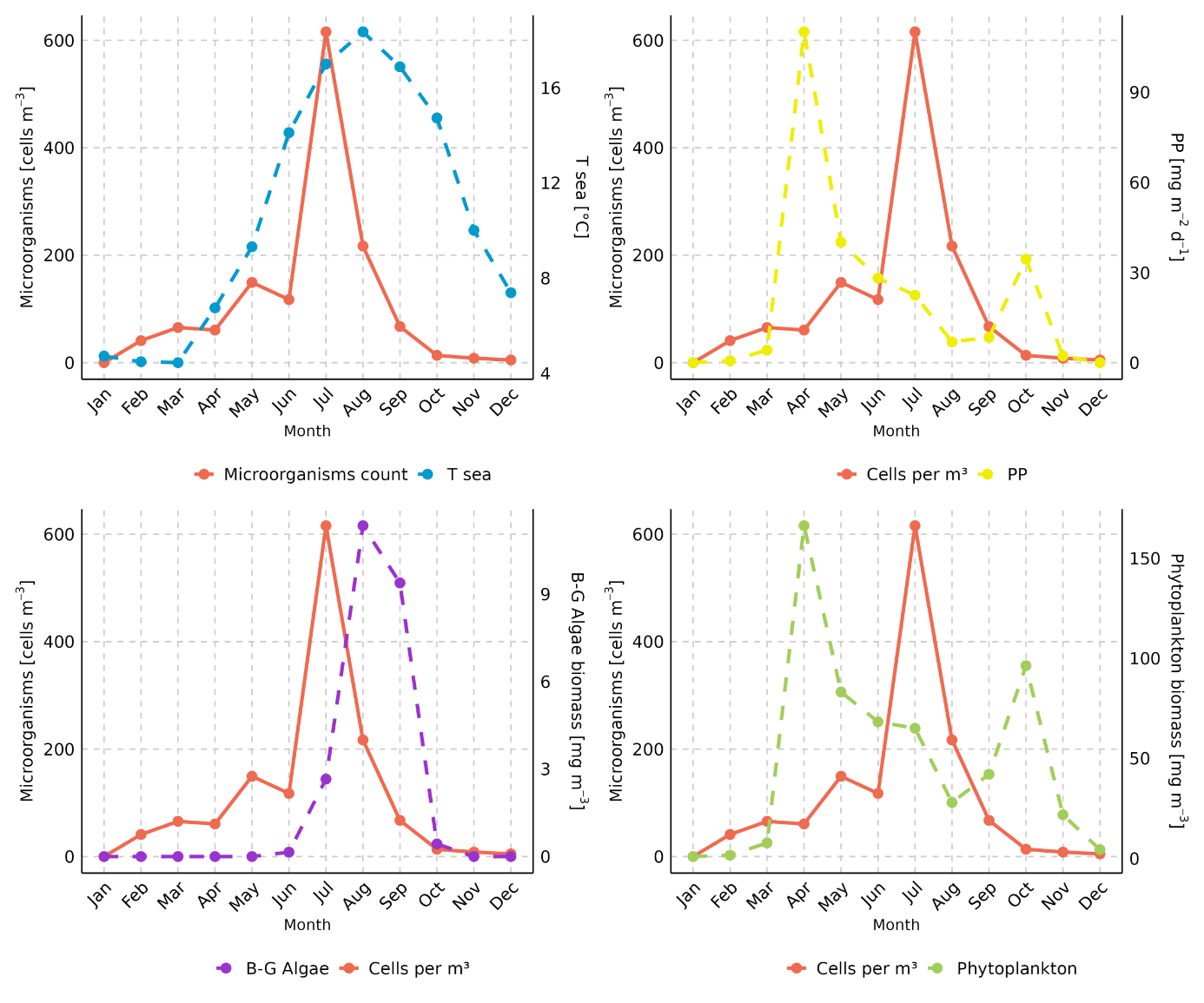
Building on this knowledge, we hypothesized that an extended phytoplankton growing season in the Baltic Sea could result in the year-round presence of airborne cyanobacteria and microalgae along the coastal zone, including winter months. This assumption is supported by research conducted in 2020 by Wiśniewska et al. (2022a). The year-long study, spanning from January to December 2020, confirmed the presence of airborne cyanobacteria and microalgae from six distinct phyla (Cyanobacteria, Chlorophyta, Heterokontophyta, Dinoflagellata, Haptophyta, and Charophyta) over the urbanized southern Baltic Sea region. Based on their frequency, these organisms were categorized into four main groups: Cyanophyta, Chlorophyta, and others (Wiśniewska et al., 2022a).

To validate these findings, we incorporated in the study the data from our other published works within the region, starting in 2015 (Lewandowska et al., 2017; Wiśniewska et al., 2022b) as well as previously unpublished data obtained in 2018 and 2019 (Fig. 1). In 2020, research was conducted throughout the year. Monthly observations consistently confirmed the year-round presence of cyanobacteria and microalgae (Fig. 1a and b), even during the winter months.



**Fig. 1 | The presence of cyanobacteria and microalgae in the air throughout the year. a** The dominant division and frequency of the presence of airborne cyanobacteria and microalgae during the measurement period. Here, a year-long analysis (i.e. sampling every month) was conducted in the southern Baltic Sea in 2020. In previous years, research was conducted in selected months while months for which no research was conducted were marked as NA. **b** The percentage share of individual groups of airborne cyanobacteria and microalgae collected in southern Baltic Sea coast from 2015 to 2020.

Interestingly, although the presence of these microorganisms, at least in coastal regions, is closely linked to meteorological factors, particularly air temperature. Their winter presence has also been confirmed in Bratislava (Žilka et al., 2023), however no significant seasonal differences in abundance were recorded by authors. Although the peak of primary production in the Baltic Sea occurred before the peak abundance of cyanobacteria and microalgae in the atmosphere, the variability pattern confirms that, particularly from November to March, the number of organisms in the atmosphere is closely linked to primary production in the sea. Interestingly, the highest number of cyanobacteria and microalgae cells in 2020 was recorded in July—after the peak increase in phytoplankton but before the peak growth of cyanobacteria. July was the month when a high taxonomic diversity was noted in the atmosphere, without the dominance of any particular group (Fig. 2). This indicates that the maximum number of cells in the air occurred in the middle of the cycle—when the amount of cyanobacteria cells in the sea was high (approaching its maximum in August). In addition to that the concentration of phytoplankton, including other microalgae, remained high as it stabilized after the spring peak.

**Fig. 2 | Monthly variation of cells number of airborne microalgae and cyanobacteria and sea parameters.** T sea [ºC] – sea temperature, PP [mg m-2 d-1] – primary production, B-G Algae [mg m-3] – cyanobacteria concentration in the sea, and phytoplankton biomass [mg m-3].

Scientific research confirms that global warming in the case of the Baltic Sea appears to affect primary production in several interlinked ways (Viitasalo and Bonsdorff, 2022). On one hand, warming extends the phytoplankton growing season; on the other hand, warming-induced changes in stratification and nutrient dynamics may favor summer cyanobacterial blooms (Viitasalo and Bonsdorff, 2022). Consequently, an increase in the abundance of cyanobacteria in the atmosphere can also be expected.

Moreover, studies conducted both in the Baltic Sea region and in other parts of the world have confirmed that the taxonomic composition of cyanobacteria and microalgae undergoes seasonal variations (Sharma et al., 2006; Wiśniewska et al., 2022a). These changes are not limited to fluctuations in the number of recorded taxa but also encompass shifts in their relative abundance throughout the year. Therefore, it is difficult to clearly determine which division dominates in a given climate zone. The dominance of individual groups does not have to be a constant phenomenon (Fig. 1b). This may result from various sources of bioaerosols, such as water bodies or terrestrial environments, as well as changing meteorological factors. Therefore, detecting such patterns requires at least several years of sampling. Thus, it remains valid that, regardless of location, Cyanobacteria are consistently detected in the atmosphere worldwide (Wiśniewska et al., 2019).

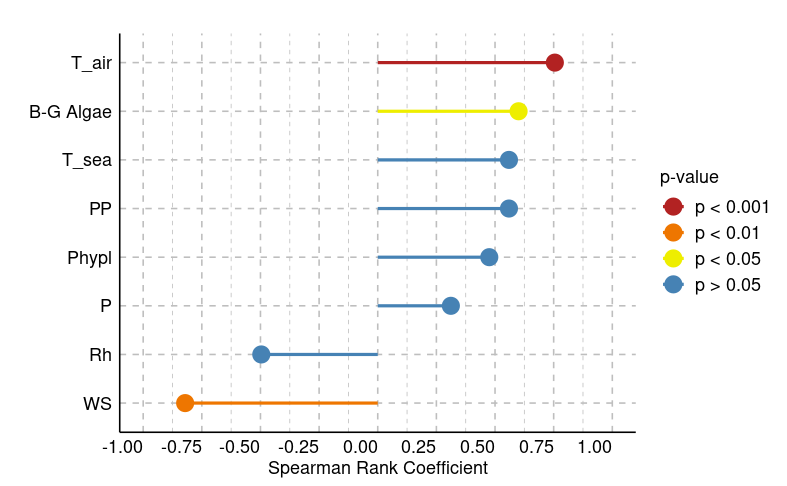
The number of cyanobacteria and microalgae cells in the atmosphere over southern Baltic Sea was determined only during the studies conducted in 2020 (Wiśniewska et al., 2022a), with the number of cyanobacteria and microalgae ranging from zero to 1685 cells m⁻³. A review by Després et al. (2012) states that the concentration of microalgae and cyanobacteria in the air varies between 100 and 1000 cells m−3 that is consistent with presented results. While Reisser (2001) reported the presence of 300-500 cells m⁻³ of microalgae and cyanobacteria that we inhale on sunny summer days. In 2020, the highest average number of taxa recorded in the air occurs in July and then decreases (Fig 1). We showed that in the atmosphere of study area, airborne cyanobacteria or green algae alternately dominate, and they can also be expected in the winter months. Additionally, cyanobacteria dominate in August, which is closely related to the occurrence of toxic cyanobacterial blooms in the southern Baltic Sea area (Wiśniewska et al., 2022a) (Fig. 2).

In the coastal zone of the southern Baltic Sea during the winter period, only cyanobacteria and green algae were detected, with no significant dominance of any of this group (Fig. 1b). Moreover, during examined period of winter, the number of airborne microorganisms was relatively low. For instance, in January 2020, only 2 taxa were recorded, and the average number of cells was equaled to 3.47 cells m⁻³, while in February the number of cells increased up to 41 cells m⁻³ on average.

With regional projections indicating that the annual mean near-surface temperature in the Baltic Sea region could rise by 1.4°C to 3.9°C by the end of this century compared to 1976–2005 (Gröger et al., 2021), it is anticipated that taxa typically associated with spring may increasingly be recorded during the winter months. Conversely, rising winter temperatures may enhance the appeal of the region for tourism, even during the winter season. However, the ongoing increase in temperatures that favors more frequent cyanobacterial blooms may extend human exposure to these organisms and their toxins beyond the summer months. Similar to the case of pollen, the extension of the growing season due to climate change may lead to prolonged exposure to airborne cyanobacteria and microalgae (Dąbrowska-Zapart et al., 2018). This could increase sensitization and exacerbate the prevalence and severity of symptoms associated with respiratory conditions, as has been observed with seasonal allergic diseases (Choi et al., 2021).

**Meteorological factors vs. the amount of cyanobacteria and microalgae in the air**

Meteorological parameters impact the abundance and taxonomic diversity of cyanobacteria and microalgae in atmospheric aerosols throughout the coastal zone of the Baltic Sea (Wiśniewska et al., 2022a; Wiśniewska et al., 2022b). The primary meteorological factors include air temperature and humidity, wind speed and direction, air mass advection, precipitation, and the duration of available light (photoperiod). Depending on the prevailing weather conditions, cyanobacteria and microalgae may be released into the atmosphere from water bodies or remitted from various surfaces (Rosas et al., 1989b; Sharma et al., 2006; Singh et al., 2018). This process is most efficient during periods of high primary productivity (Wiśniewska et al., 2022a; Wiśniewska et al., 2022b). Certain meteorological factors can facilitate the transport of these microorganisms across land or contribute to their removal from the atmosphere (Lewandowska et al., 2017; Sharma & Singh, 2010; Wiśniewska et al., 2019; Wiśniewska et al., 2022a; Wiśniewska et al., 2022b; Wiśniewska et al., 2023).   
 The findings from our studies suggest that an increase in air temperature can stimulate the presence of cyanobacteria and microalgae in the atmosphere, analogous to its effect on enhancing phytoplankton biomass in the sea. In the coastal zone of the southern Baltic Sea, a strong positive proportional relationship (Spearman rank correlation coefficient 0.755, p value<0.001) has been observed between the quantity of airborne cyanobacteria and microalgae and air temperature (Wiśniewska et al., 2022a) (Fig. 3).



**Fig. 3 | Spearman’s rank correlation coefficients and their statistical significance between the number of cyanobacteria and microalgae cells and environmental parameters,** including air temperature (T\_air), cyanobacteria biomass in the sea (B-G Algae), sea temperature (T\_sea), primary production (PP), phytoplankton biomass (Phypl) atmospheric pressure (P), relative humidity (Rh), and wind speed.

Wind speed is a crucial meteorological factor influencing both the abundance and taxonomic diversity of cyanobacteria and microalgae in the atmosphere, as observed globally and specifically also in the Baltic Sea region (Lewandowska et al., 2017; Wiśniewska et al., 2019; Wiśniewska et al., 2022a; Wiśniewska et al., 2022b) (Fig. 3). Wind facilitates the drying, fragmentation, and airborne transport of algae. Generally, the impact of wind is similar for both bioaerosols and other particulate matter in the air. Higher wind speeds enhance the production of bioaerosols and enable their transport over greater distances (Sharma et al., 2006b; Lewandowska et al., 2017).

The significant correlation which we found in our measurements was that rainfall had a reduced ability to remove cyanobacteria and microalgae when relative humidity rose during the day (Wiśniewska et al., 2022b). The study's findings showed that, of all the meteorological parameters, rainfall seems to have the greatest impact on the quantity of cyanobacteria and microalgae in the air above the coastal zone of the Baltic Sea (Wiśniewska et al., 2022b). There are two main ways that rainfall impacts these microorganisms' existence. First, microalgae and cyanobacteria can be successfully removed from the atmosphere by rainfall. Our previous results demonstrated that, in comparison to their pre-rainfall values, the quantity of cyanobacteria and microalgae cells in aerosols decreased by 21–87% after each rainfall event (Wiśniewska et al., 2022b). This decrease is noteworthy, particularly considering the roughly 40% drop in atmospheric bacteria that was noted during washout procedures (Ouyang et al., 2020). Rainfall, however, has the opposite effect of increasing the taxonomic variety of algae on land and in the ocean. Raindrops can remove microalgae and cyanobacteria from clouds and terrestrial object surfaces such as tree leaves (Schlichting, 1969; Dillon et al., 2020). Furthermore, rainfall may encourage the re-emission of microalgae and cyanobacteria that have already been emitted into the atmosphere (Joung et al., 2017; Wiśniewska et al., 2022b). Research carried out in the coastline zone of the southern Baltic Sea revealed that there can be differences in the taxonomic composition of microalgae and cyanobacteria in the atmosphere between before and after rainfall. However, brief rainstorm events did not fully eliminate any one taxon from the atmosphere. *Synechococcus* sp. was an exception to this rule, completely wiped-out during rainstorm episodes that lasted longer than twenty-four hours. Furthermore, it was discovered that some taxa, including *Nodularia* cf. *harveyana*, that were not discovered in aerosols prior to the rain may be present in the downpour (Wiśniewska et al., 2022b).

This fluctuation may be linked to the nearly daily variations in the air mass trajectories' directions, which facilitate the introduction of additional microorganism species from marginally distinct source locations. Additional research has shown that alterations in the air mass passing over the measuring station can be linked to the occurrence of fresh microalgae in samples (Lewandowska et al., 2017; Wiśniewska et al., 2020; Wiśniewska et al., 2022b). One of the most important meteorological factors impacting the quantity and taxonomic diversity of cyanobacteria and microalgae in the air above the coastal zone is the direction of air mass advection, coupled with wind speed. Long-distance microbe transportation is caused by this factor (Lewandowska et al., 2017; Wiśniewska et al., 2020).

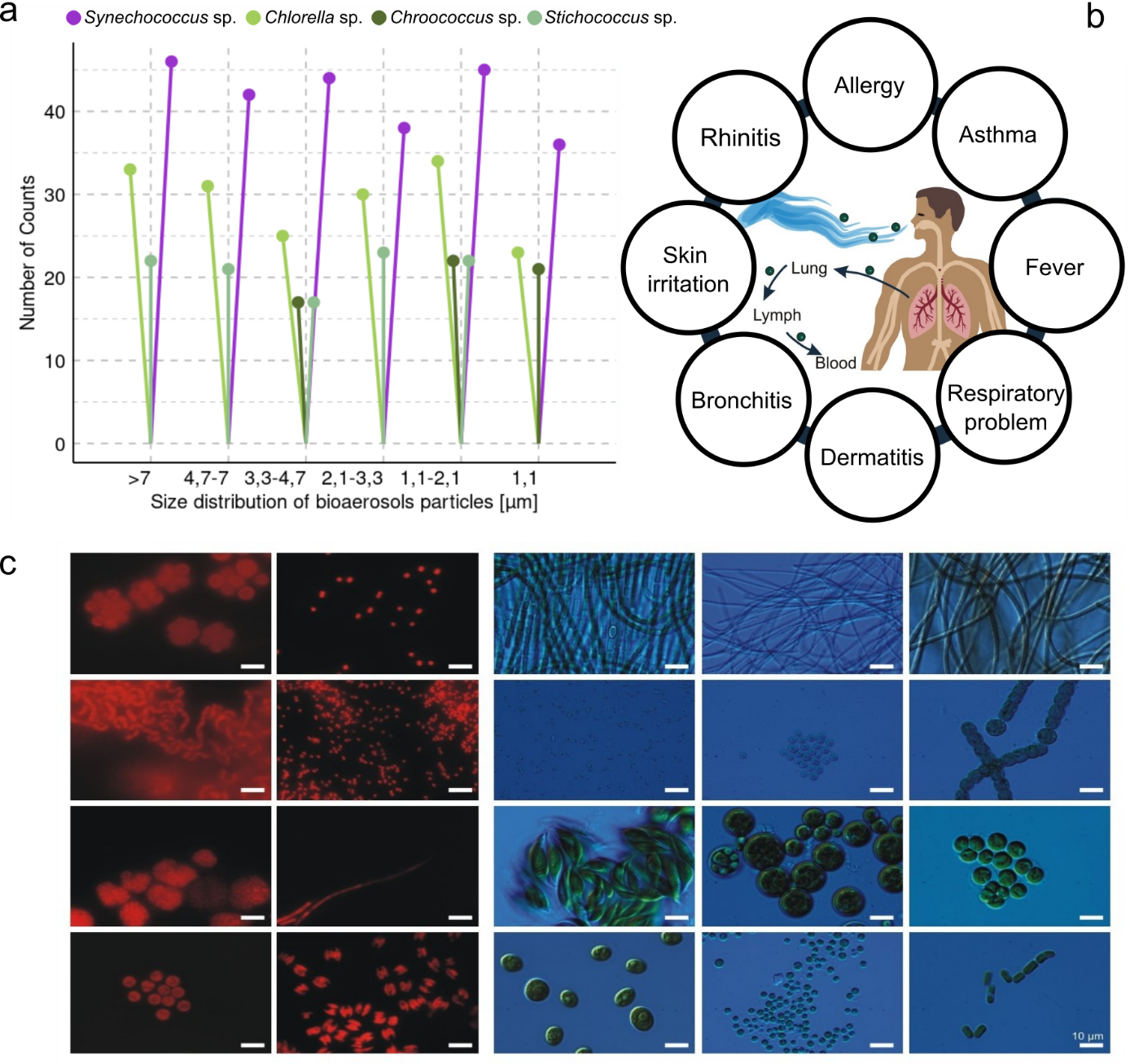
**Cyanobacteria and microalgae suspended in the air can pose a potential threat to human health**

Air quality is now acknowledged as one of the most critical environmental threats, impacting animal and human health. The presence of chemical substances in the atmosphere has been a major focus of scientific research for last two decades. Significant research efforts have been dedicated to this issue, as detailed by Manisalidis et al. (2020).

Genitsaris et al. (2011) created a list of cyanobacteria and microalgae found in the atmosphere that might be harmful to humans if breathed. 29 species of airborne cyanobacteria and microalgae were discovered in 2020 during study in the Baltic Sea coastal zone (Wiśniewska et al., 2022a). Among these, several taxa—including *Amphora* sp., *Bracteacoccus* sp., *Chlorococcum* sp., *Chlorosarcinopsis* sp., *Oocystis* sp., *Stichococcus* sp., *Nodularia* sp., *Nostoc* sp., *Synechocystis* sp., *Chrysochromulina* sp., and *Gymnodinium* sp. were identified as potentially harmful to human health when inhaled (Wiśniewska et al., 2022a). When these organisms penetrate the human respiratory system with aerosols, they can lead to a variety of symptoms, including headaches, nausea, dizziness, allergic responses, exacerbations of asthma, skin rashes, eye irritation and redness, and neurotoxic effects (Fig. 4). They can also produce toxins, as confirmed by studies conducted in the coastal zone of the southern Baltic Sea (Wiśniewska et al., 2022a). Currently, there is no scientifically established data on the quantity of toxins that must be inhaled to cause adverse health effects in humans. However, there are studies that confirm that the presence microalgae in the atmosphere negatively affects the function of human lungs (Dales et al., 2025).

Some researchers have confirmed that microcystin-LR (MC-LR) can have toxic effects on organisms even at lower doses when inhaled (Sahu and Tangutur, 2014). Due to this, MC-LR was selected as the indicator toxin. MC-LR, a well-known hepatotoxin, is one of the most studied toxins produced by cyanobacteria. MC-LR are known not only to damage liver function but also to promote the formation of liver tumors and induce cell death in hepatocytes through apoptosis and necrosis (Rzymski, 2009). In our study, the concentrations of MC-LR varied from levels below the detection threshold up to 420 fg cell−1 (Wiśniewska et al., 2022a). Various cyanobacterial strains, including *Nostoc* sp., *Nostoc edaphicum*, *Pseudanabaena galeata*, *Pseudanabaena catenata*, *Leptolyngbya* sp., *Synechococcus* sp., *Gloeocapsa* sp., and *Rivularia* sp. were found to contain MC-LR. The peak concentration of this toxin (420 fg cell−1) was noted in the picocyanobacterium *Synechococcus* sp. (Wiśniewska et al., 2022a). It is notable that *Synechococcus* sp. is one of the most ubiquitous photoautotrophic microorganisms on Earth (Whitton and Potts, 2000). Nevertheless, it's crucial to emphasize that various species or strains within the same genus might have differing toxin production levels (Wiśniewska et al., 2022a). Generally, during algal blooms, there is an increased chance of breathing in hazardous organisms and their poisons (Wiśniewska et al., 2019, Wiśniewska et al., 2022a). According to our research, May 2020 was the month with the greatest MC-LR concentrations (Wiśniewska et al., 2022a). On the other hand, aerosols from a major cyanobacteria bloom in the coastal zone of the southern Baltic Sea in August 2020 revealed the presence of *Nodularia* sp., a cyanobacterium that is known to pose health risks. Toxic cyanobacteria blooms and nodularin production typically take place in the summertime in the measuring region (Lehtimaki et al., 1997; Paldaviciene et al., 2009). The amount of MC-LR in the atmosphere was found to be lower in August than in May, although it was still present in species from the genus *Synechococcus*, *Chroococcus*, *Nodularia*, *Phormidium*, and *Pseudanabaena*. As a result, it is advised that sensitive people, including those with asthma or inhalant allergies, stay out of the Baltic Sea's coastline zone for as long as possible when there are strong algal blooms.

The relationship between bioaerosols' size and deposition in the human respiratory system is another important topic to scientific research. Smaller bioaerosols are predicted to enter the human respiratory system more deeply than particulate matter (PMx) and to settle in the bronchial and acinar airways, where they will cause a variety of diseases (Fröhlich-Nowoisky et al., 2016; Lewandowska et al., 2017; Facciponte et al., 2018). To quantitatively assess the presence of airborne algae and cyanobacteria, a six-cascade impactor was employed as a surrogate for the human respiratory tract (Wiśniewska et al., 2019). It could gather particles in six size ranges (> 7 μm, 4.7–7 μm, 3.3–4.7 μm, 2.1–3.3 μm, 1.1–2.1 μm, and ≤1.1 μm) with the proper diameter. Studies carried out in the coastal zone of the Baltic Sea revealed that, of all the coarse particles (> 2.1 μm) present in bioaerosols, the total number of cyanobacteria and microalgae cells was the largest, accounting for 61% of all the cells (6901 cells m−3). This size of particle can be found in the upper respiratory system, although it can only get as far as the secondary bronchi.

**Fig. 4 | Airborne cyanobacteria and algae affecting human health. a** The occurrence of selected airborne cyanobacteria and microalgae in different cell size classes. **b** The most frequently recorded species of airborne cyanobacteria and microalgae from the air. **c** Effects of the penetration of airborne cyanobacteria and microalgae of various sizes into the human body.

The most hazardous taxa were found in coarser particles, which don't get to the deeper reaches of the respiratory system. The number of microalgae and cyanobacteria, however, did not change statistically significantly based on the size distribution of the bioaerosol (Kruskal Wallis test, *p* > 0.05). This suggests that individual organisms cannot be assigned to a single size fraction.

The cause of this might be because the diameter of the coccoid algae varies from a few to several dozen μm, affecting the size of organisms that fit through the impactor nozzles at a particular diameter. When it comes to filamentous organisms, the problem becomes more intricate because their length and breadth vary from a few to several μm. Consequently, a shorter plane-arranged organism can enter nozzles with a smaller diameter and land deeper into the human respiratory system. Therefore, it should be taken into consideration that these organisms can enter human alveoli in the event of substantial emissions of poisonous cyanobacteria and microalgae, such as during hazardous cyanobacterial blooms (Wiśniewska et al.,

Moreover, studies on avian influenza, measles, and SARS (including COVID-19) have highlighted that viruses and bacteria can pose a greater health risk when present in polluted air (Cu et al., 2003; Su et al., 2019; Frontera et al., 2020; Peng et al., 2020; Yao et al., 2020; Annesi-Maesano et al., 2021; Pansini et al., 2021), it is crucial to explore the potential impact of cyanobacteria and microalgae in these contexts (Wiśniewska et al., 2023). The threat to human health is greater the more toxic and dangerous compounds there are in the air. Such chemical compounds include benzo(a)pyrene, commonly recognized as a significant air pollutant in many parts of the world, including the southern Baltic Sea. Because of its carcinogenic, mutagenic, and poisonous qualities, this chemical is particularly dangerous (Tobiszewski and Namieśnik, 2012). Benzo(a)pyrene is classified as a Group 1 carcinogen by the International Agency for Research on Cancer (IARC), signifying a high potential for human cancer. The allowable yearly average concentration of this chemical in PM10 has been determined by the European Union at 1 ng m−3 (Directive 2004/107/EC). The Gdynia region has one of the lowest levels of benzo(a)pyrene pollution in Poland, but even in aerosols with the smallest diameter, the daily concentration of this pollution surpasses the annual standard several times a year (e.g., Staniszewska et al., 2013, Wiśniewska et al. 2019b). In our previous studies we focused on the relationship between human health and benzo(a)pyrene in the air and cyanobacteria and microalgae (Wiśniewska et al., 2023). In a laboratory experiment different concentrations of benzo(a)pyrene were applied to selected strains of cyanobacteria and microalgae that were isolated from the atmosphere. The concentrations ranged from relatively low (standard solution of 7.8 ng L−1, equivalent to 0.5 ng m−3 in the air) to very high (standard solution of 624 ng L−1, equivalent to 40 ng m−3 in the air). g m−3 in the atmosphere) to extremely high concentrations (standard solution of 624 ng L−1, or 40 ng m−3 in the atmosphere). It's interesting to note that none of the strains were destroyed by the addition B(a)P, which is extremely harmful to humans (Wiśniewska et al., 2023). Moreover, several cyanobacteria and microalgae exhibited changes in the quantity of assimilatory pigments, a rise in cell population, and the ability to perform photosynthesis upon the addition of even low concentrations of B(a)P. Thus, benzo(a)pyrene-induced air pollution, even at low concentrations, is expected to promote the proliferation of airborne cyanobacteria and microalgae. We also aimed to determining if cyanobacteria and microalgae could break down the benzo(a)pyrene already present in the air. When comparing the concentration of benzo(a)pyrene in the presence of green algae to cyanobacteria and diatoms, it was observed that there was a notable variation at the conclusion of the experiment (Wiśniewska et al., 2023). The potential for cyanobacteria and diatoms to degrade benzo(a)pyrene remains an area requiring further research. However, our results indicate green algae can degrade even up to 80% of benzo(a)pyrene. This finding aligns with existing scientific literature (Warshawsky et al., 1995; Alegbeleye et al., 2017).

However, it is worth noting that while in the case of many bioaerosols there are studies indicating the relationship between biological particles and air pollution, in the case of cyanobacteria and microalgae such studies are still lacking. However, Žilka et al. (2023) in Slovakia demonstrated significant negative dependency between the concentration of bioaerosols, such as microalgae and cyanobacteria, and air pollution concentration, particularly CO, NO₂, and PM10. High concentrations of carbon monoxide can inhibit the growth of source algae, while elevated nitrate levels may restrict the development of cyanobacteria. At the same time, tropospheric ozone generally shows positive correlations with the concentration of airborne microorganisms, suggesting that it may contribute to their presence. A particularly important observation is that the simultaneous increase in the concentration of microorganisms and ozone may exacerbate symptoms of respiratory allergies in urban areas (Žilka et al. 2023).

This raises the question of whether the concentration of benzo(a)pyrene in the air in coastal areas such as northern Poland is significantly reduced compared to other regions of Central Europe due to the presence of green algae. Would the absence of green algae result in higher concentrations of this hazardous chemical compound? Future research should focus on identifying the byproducts formed when benzo(a)pyrene is decomposed by green algae. While the removal of benzo(a)pyrene from the environment might seem beneficial, the decomposition process could yield potentially harmful substances, such as peroxides, quinones, sulfur, and nitric derivatives, which might still pose risks to living organisms (Papageorgopoulou et al., 1999; Chetwittayachan et al., 2002). Despite these concerns, airborne green algae offer a promising avenue for bioremediation.

**The future of airborne microalgae and cyanobacteria research in the era of machine learning**

Conducting numerous studies on cyanobacteria and microalgae by our team over the past few years has led to many conclusions and future recommendations. Based on the data obtained and numerous interdisciplinary observations, the authors have determined how the collected data can be used to expand the existing state of knowledge using modern machine learning techniques. By identifying the gaps in these studies, many recommendations for future applications of machine learning research can be made. One of the biggest problems concerning the research on cyanobacteria and microalgae is the non-ergonomic techniques for determining the quantity and taxonomic composition of microorganisms (Wiśniewska et al., 2019). A significant improvement in these studies would be conducting such analyses online using automatic bioaerosols sensors (Sauvageat et al., 2020; Erb et al., 2024,González-Alonso et al., 2024). Automatic monitors are increasingly being utilized in research, primarily for the analysis of atmospheric pollen. However, efforts are also being made to extend these methods to the study of fungi (Erb et al., 2024). Current technologies employing holographic imaging of bioaerosols, combined with particle fluorescence analysis, demonstrate potential for application in the investigation of airborne cyanobacteria and microalgae (Lieberherr et al., 2021), For example, picoplanktonic cyanobacteria can reach sizes as small as approximately 0.2–2 µm, whereas the Swisens Poleno is primarily designed for larger particles but operates effectively from 2 µm onward.

However, in order to train the system to recognize specific particles, it is essential to have well-characterized particle banks. These reference libraries consist of known bioaerosol samples, including pollen, fungal spores, cyanobacteria, and microalgae, which serve as training data for the machine learning algorithms. Without such databases, the system would lack the necessary information to accurately classify airborne particles based on their holographic images and fluorescence spectra. Establishing comprehensive particle banks is therefore a crucial step in enhancing the accuracy and reliability of automated bioaerosol monitoring. The more accurately the taxonomic composition is determined, the better the accuracy, so it would be advisable to conduct genetic studies.

**Conclusion**

This study reveals differences in the impact of meteorological parameters based on the geographical location. In addition to air temperature and wind speed, the prevalence of cyanobacteria and microalgae in the coastal zone is significantly influenced by factors directly related to the sea, including primary production and phytoplankton

Between analysed taxa, the green algae species demonstrated the highest potential for B(a)P degradation, thereby suggesting a promising avenue for bioremediation. At low levels of benzo(a)pyrene concentrations cyanobacteria and microalgae can have considerable implications for the advancement of biotechnology. On the other hand, we lack knowledge about the substances into which compounds degraded by green algae break down and whether these degradation products might pose a greater risk to health than the original compound.

**Data availability**

Data supporting this study is available on: https://github.com/FundyPhytoPhys/SynBaltic/Airborne (public GitHub Repository).

Code to perform data processing and analyses is available at https://github.com/FundyPhytoPhys/SynBaltic/Airborne.

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**Competing interests**

The authors declare no competing interests

**Additional information**

**Supplementary information** …

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