Co-occurrence of airborne biological and anthropogenic pollutants in the central European urban ecosystem

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Abstract
The interactions between organic and inorganic air pollutants, enhanced by the impact of weather parameters, may worsen the respiratory allergy symptoms in allergy sufferers. Pollen grains and fungal spores belong to some of the most crucial aeroallergens. Other allergenic bioparticles in the atmospheric microbiome can include microalgae, fern spores and mites. In this study, we evaluated if and to what extent air pollutants and weather parameters drive the daily variation in airborne concentrations of a broad spectrum of bioparticles (pollen grains, fungal spores, microalgae, fern spores and invertebrates) in the air of Bratislava over 3 years, 2019–2021. Air samples were collected using a Hirst-type volumetric sampler. Based on the results of Spearman’s correlation analysis, air temperature seems to be the most influential meteorological factor, positively associated with the concentration of all types of bioparticles at assemblage level, even though the association with microalgae was negative. Wind speed, known to have a diluting effect on most airborne particles, appears to be the most influential for microalgae, as their concentration in the air increases along with rising wind speed. Considering air pollutants, correlation analysis revealed that as the daily concentrations of ozone, PM10, CO and/or NO2 increased, so did the levels of most types of analysed bioaerosols at the assemblage level. Regarding that bioparticles may act as carriers for inorganic particles and amplify their allergenic impact, a concomitant increment in the airborne concentration of both organic and inorganic pollutants poses a threat to allergy sufferers in the study area. The concentration of microalgae, on the other hand, decreases with rising levels of CO, NO2 and PM10; thereby, their synergistic effect on allergy sufferers is negligible. Based on our findings, we suggest that the response of pollen and fungal spore concentration to environmental conditions should be investigated at the taxon, not the assemblage level, as each pollen/spore taxon has a different pattern in response to meteorological parameters and air pollutants.

Keywords Air pollutants · Pollen · Fungal spores · Fern spores · Microalgae · Invertebrates

Introduction
Air is the common transport medium for viruses, bacteria, algae, cyanobacteria and reproductive structures of seed plants (pollen grains), seedless plants and fungi (spores). Besides, small invertebrates, mainly arthropods (e.g. insects, mites and spiders), are also passively transported by air currents (Reynolds et al. 2014). Several aspects of human life are affected by airborne bioparticles, as many are human, plant or animal pathogens, and, as such, have main implications for public health, agriculture and forestry (Desprès et al. 2012). Most airborne pollen grains and fungal spores are infamous for their allergenic potential (Taketomi et al. 2006; D’Amato et al. 2007; Levetin et al. 2016). Besides, some fern spores, microalgae and microarthropods also contain allergenic molecules capable of eliciting allergic reactions in susceptible individuals (Calderón et al. 2015; Rodríguez de la Cruz et al. 2018; Wiśniewska et al. 2019). However, due to the time-consuming quantification process, determination difficulties or low abundance in atmospheric samples, these bioparticles have yet received only marginal...
attention from aerobiologists (Melo et al. 2014; Tesson et al. 2016; Ščevková et al. 2022).

People living in urban areas are more likely to suffer from some form of respiratory allergy, or their symptoms are more severe compared to people living in rural environments (D’Amato et al. 2010; Torres et al. 2018). One of the fundamental causes is the higher proportion of anthropogenic (chemical) pollutants, e.g. particulate matter, ozone, carbon monoxide and nitrogen dioxide in urban air, capable to harm human health, especially the respiratory system (Kim et al. 2018; Xue et al. 2020) or affect the plants and fungi themselves (Ghiani et al. 2012; Rai 2016). Under the influence of pollutants, some plants and fungi produce either pollen/spores with a higher proportion of allergenic molecules (Lang-Yona et al. 2016; Ščevková et al. 2020; Ziemianin et al. 2021) or new types of allergens as a consequence of their defence mechanisms against stress factors, such as pollutants (Suárez-Cervera et al. 2008; Ribeiro et al. 2017). For instance, Ziemianin et al. (2021) and Ščevková et al. (2020) noticed that elevated ozone and PM10 levels lead to higher levels of Bet v 1 and Phl p 5 allergens, respectively, while Ribeiro et al. (2017) noted modification in the structure of lipids, proteins and polysaccharides in Platanus × acerifolia pollen due to higher ozone concentrations. Similar to plants and fungi, even algae and microarthropods could produce more or new types of allergens in response to the stress effect of pollutants. However, such impact has not yet been considered or measured. Last but not least, the interactions between biological and non-biological particles in the atmosphere play a crucial role in the incidence of respiratory allergic diseases. Chemicals in the air can facilitate the release of allergenic molecules or sub-pollen particles containing allergens from pollen grains, spores or algal cells directly into the air (Azzazy 2016), which due to their small size (0.6–2.5 µm), enter the lower respiratory tract (Motta et al. 2006). Moreover, airborne chemicals can become the carriers of allergen-bearing small particles, thus forming “complex particles” with the potential to evoke severe allergic manifestations (Cecchi et al. 2010).

To comprehensively assess the epidemiological situation and development of respiratory allergic diseases, it is necessary to consider a broad spectrum of aeroallergens and their interactions with chemical air pollutants and meteorological factors. Several studies concerning the association between organic and inorganic air pollutants have been conducted in the central European environment (Puc and Bosiacka 2011; Puc 2011; Grinn-Gofroń et al. 2011; Ščevková and Kováč 2019; Grewling et al. 2019). However, none of the existing papers has examined the relationship between air pollutants and bioaerosols other than pollen grains and fungal spores. Therefore, this study aimed to investigate the impact of inorganic air pollutants (ozone, PM10, CO and NOx) and meteorological parameters (temperature, relative humidity, precipitation and wind speed) on airborne levels of organic particles (pollen grains, fungal spores, fern spores, microalgae and invertebrates) in a medium-sized city in Central Europe.

Materials and methods

Study area

Bratislava (48° 08′ N, 17° 06′ E) is a city located in southwest Slovakia (Central Europe) on the boundary between the Malé Karpaty Mountains and the Pannonian Lowland. The urban area of 367.6 km² is comprised of farmland areas (141.2 km²); deciduous Carpathian forests dominated by Quercus sp., Carpinus betulus L. and Fagus sylvatica L., and alluvial forests dominated by Ulmus sp., Fraxinus sp., Salix sp. and Populus sp. (159.4 km² altogether with expanses of water); and developed land (67.1 km²) (Feráková and Jarolímek 2011). The climate is temperate continental with a mean annual temperature of 10.8 °C and a mean annual rainfall total of 685.5 mm (1983–2021 average, data from the meteorological observatory of the Department of Astronomy, Physics of the Earth and Meteorology of the Comenius University in Bratislava).

Aerobiological data

Airborne bioparticles, including pollen grains, fungal and fern spores, microalgae and microscopic invertebrates, were sampled from February to October over 3 consecutive years, 2019–2021, by using a Hirst-type volumetric sampler (Burkard Manufacturing Co Ltd.) (Hirst 1952). The sampler was located on the rooftop of the building (48° 08′ 58″ N, 17° 04′ 24″ E) at 18 m above ground level. Airborne samples collected at this altitude are well mixed due to dynamic air circulation and contain a mixture of both local and long-distance transported bioparticles (Lacey and West 2006). The cut-point of the Hirst-type sampler is 5.2 l/min (Willeke and Macher 1999); therefore, the collection efficiency is high for particles with an aerodynamic diameter greater than 5.2 µm, including microarthropods, pollen grains, fern spores, microalgae and most fungal spores.

Air is drawn into the device through a narrow slit at a speed of 10 l/min and hits a rotating drum which is covered with melinex tape coated with the adhesive medium. The drum rotates along the slit at a speed of 2 mm/h through a clockwork mechanism. It rotates 360° in 7 days. The exposed tape is changed once a week (always at the same time) and cut into sections corresponding to a 24-h exposure. Each segment of tape is placed on a gelatin-glycerin-coated microscope slide and covered with a coverslip (Galán et al. 2007; 2014). The bioparticles were counted in 12 transversal
analyses were performed in Statistica 12.

tal variables has been studied by linear regression analysis and Spearman's correlation coefficients, reflecting the extent of correlation. The data analyses were performed in Statistica 12.

Environmental data and statistical analysis

The following meteorological parameters, recorded at the meteorological observatory of the Comenius University in Bratislava (48° 09' 04" N, 17° 04' 14" E, 182 m a.s.l.), were taken into consideration: T, temperature (°C); S, sunshine (h); RH, relative humidity (%); P, precipitation (mm); and WS, wind speed (m/s). The meteorological observatory is situated 1 km NW of the sampling site. The atmospheric pollutants incorporated in the present study were provided by the Slovak Hydrometeorological Institute (SHMÚ). The parameters were as follows: O₃, ground-level ozone (µg/m³); PM₁₀, particulate matter ≤ 10 µm (µg/m³); CO, carbon monoxide (µg/m³); and NO₂, nitrogen dioxide (µg/m³).

The relation between the mean daily concentrations of individual airborne bioparticles and selected environmental variables has been studied by linear regression analysis and by establishing non-parametric Spearman’s correlation coefficients, reflecting the extent of correlation. The data analyses were performed in Statistica 12.

Results

We observed 48 types of bioparticles (29 pollen grains, four fungal spores, seven fern spores, one microalgae and six invertebrates) in the present study (Table 1). The greatest total concentration of bioparticles was attributed to fungal spores, representing the annual totals from 117,901 spore*day/m³ in 2019 to 205,984 spore*day/m³ in 2021. Other abundant bioparticles were pollen grains with the prominent contribution of arboreal pollen, with the levels ranging from 27,252 pollen*day/m³ in 2019 to 44,534 pollen*day/m³ in 2020. The annual totals of herbaceous pollen reached the values from 9981 pollen*day/m³ in 2019 to 15,837 pollen*day/m³ in 2020. Microalgae were also abundant, with contributions of 24,342 and 18,060 cell*day/m³ in 2020 and 2021, respectively. Fern spores and invertebrates contribute only marginally to the spectrum of airborne bioparticles in the study area (Table 1).

The monthly variations of the airborne concentrations of individual groups of bioparticles in Bratislava are depicted in Fig. 1. In winter and spring, microalgae and arboreal pollen, respectively, were abundantly represented in the air of the study area, while in summer and autumn, herbaceous pollen and fungal spores were the main contributors. The highest occurrence of fern spores and invertebrates in the air was also linked to summer and autumn, although less abundant.

The quantity of all bioparticles considered (except microalgae—not quantified in 2019 and fern spores) was significantly lower in 2019 than in the next 2 years (Fig. 2). However, only pollen and microalgae were more abundant in 2020 compared to the following year. The concentrations of individual bioparticles were from 24 to 65% higher in 2020 and from 18 to 85% higher in 2021 compared to 2019. The decrease in the pollen and microalgae concentrations in 2021 was 27 and 26%, respectively, compared to the previous year. On the other hand, we observed an 8% increase in the levels of invertebrates, 30% in fern spores and 41% in fungal spores in 2021 compared to 2020.

The weather, as well as the rate of air pollution, was different over the analysed years. The period from 1 February to 31 October 2019 was the warmest and driest period among the 3 years analysed (Fig. 2; Table 2). The average annual temperature and total annual precipitation of 15 °C and 732.7 mm were recorded in 2019, while in 2020 and 2021, the temperature was 0.6 and 1.4 °C lower, respectively. Moreover, the precipitation was 252.6 higher in 2020 and 46.8 mm higher in 2021 compared to 2019. Concerning air temperature, the most noticeable interannual differences were recorded in June, while for precipitation, it was in May and June (Fig. 3). Regarding anthropogenic air pollutants, a drop in the concentration of all parameters considered was observed in 2020 and 2021 compared with 2019 (Fig. 2; Table 2). This decline was related to the Covid-19 lockdowns in 2020 and 2021 caused mainly by a reduction in emissions from motor vehicles. The most pronounced drop was observed for CO, NO₂ and PM₁₀, with the average annual concentrations in 2020–2021 being 25, 18 and 12% lower than in 2019, respectively. The decrease in ozone concentration was less pronounced. The most noticeable interannual shifts in the levels of all air pollutants considered were recorded between April and June (Fig. 3).

The Spearman’s correlation coefficients calculated between daily values of bioparticle concentrations, meteorological parameters and anthropogenic air pollutants are presented in Table 3. Our results show that air temperature and relative humidity were the most influential of meteorological factors. Except for microalgae, we observed significant positive associations between the mean air temperature and the concentration of each type of bioparticle at assemblage level. However, the relationship between temperature and microalgae was negative. Significant negative associations were noted between relative humidity and all types of bioparticles at assemblage level, except for fungal spores (with significant positive correlation) and invertebrates (without significant correlation). Wind speed appears to
Table 1  Total annual concentrations and percentage contributions of individual types of bioparticles in the air of Bratislava, years 2019–2021

| Taxa             | 2019 | %   | 2020 | %   | 2021 | %   |
|------------------|------|-----|------|-----|------|-----|
|                  | Σ    |     | Σ    |     | Σ    |     |
| Arboreal taxa    |      |     |      |     |      |     |
| Acer             | 507  | 0.33| 110  | 0.05| 195  | 0.07|
| Aesculus         | 12   | 0.01| 41   | 0.02| 154  | 0.06|
| Ailanthus        | 71   | 0.05| 95   | 0.04| 195  | 0.07|
| Alnus            | 2163 | 1.39| 2622 | 1.13| 2732 | 1.02|
| Betula           | 7071 | 4.55| 9149 | 3.95| 1575 | 0.59|
| Carpinus         | 299  | 0.19| 1298 | 0.56| 283  | 0.11|
| Castanea         | 15   | 0.01| 43   | 0.02| 140  | 0.05|
| Corylus          | 181  | 0.12| 786  | 0.34| 671  | 0.25|
| Cup/Tax          | 2915 | 1.88| 3000 | 1.30| 4145 | 1.55|
| Fagus            | 185  | 0.12| 1206 | 0.52| 20   | 0.01|
| Fraxinus         | 1227 | 0.79| 8153 | 3.52| 3217 | 1.20|
| Juglans          | 125  | 0.08| 285  | 0.12| 273  | 0.10|
| Larix            | 4    | <0.01| 21  | 0.01| -    | -   |
| Pinaceae         | 3085 | 1.98| 6772 | 2.93| 6233 | 2.32|
| Platanus         | 223  | 0.14| 200  | 0.09| 129  | 0.05|
| Populus          | 4938 | 3.18| 5177 | 2.24| 6209 | 2.31|
| Quercus          | 2930 | 1.88| 3272 | 1.41| 2158 | 0.80|
| Salix            | 895  | 0.58| 1037 | 0.45| 614  | 0.23|
| Sambucus         | 73   | 0.05| 637  | 0.28| 286  | 0.11|
| Tilia            | 40   | 0.03| 225  | 0.13| 134  | 0.05|
| Ulmus            | 295  | 0.19| 405  | 0.18| 194  | 0.07|
| Total            | 27,254 | 17.53 | 44,534 | 19.25 | 29,557 | 11.02 |
| Herbaceous taxa  |      |     |      |     |      |     |
| Ambrosia         | 1910 | 1.23| 2267 | 0.98| 2038 | 0.76|
| Artemisia        | 257  | 0.17| 430  | 0.19| 214  | 0.08|
| Chenopodiaceae   | 370  | 0.24| 354  | 0.15| 425  | 0.16|
| Humulus          | 477  | 0.31| 453  | 0.20| 514  | 0.19|
| Plantago         | 542  | 0.35| 1309 | 0.57| 589  | 0.22|
| Poaceae          | 1100 | 0.71| 2048 | 0.89| 3049 | 1.14|
| Rumex            | 103  | 0.07| 232  | 0.10| 283  | 0.11|
| Urticaceae       | 5222 | 3.36| 8744 | 3.78| 7179 | 2.68|
| Total            | 9981 | 6.42| 15,837 | 6.84| 14,291 | 5.33 |
| Fungi            |      |     |      |     |      |     |
| Alternaria       | 18,875 | 12.14 | 22,024 | 9.52| 21,059 | 7.85 |
| Cladosporium     | 92,134 | 59.27 | 114,411 | 49.44| 175,565 | 65.44|
| Epicoccum        | 5237 | 3.37| 7351 | 3.18| 7626 | 2.84|
| Stenphylium      | 1655 | 1.06| 2575 | 1.11| 1734 | 0.65|
| Total            | 117,901 | 75.85 | 146,361 | 63.25| 205,984 | 76.78|
| Pteridophytes    |      |     |      |     |      |     |
| Asplenium        | 6    | <0.01| 9    | <0.01| 11  | <0.01|
| Athyrium         | 33   | 0.02| 47   | 0.02| 56   | 0.02|
| Botrychium       | 0    | <0.01| 0    | <0.01| 15  | 0.01|
| Cystopteris      | 1    | <0.01| 2    | <0.01| 3   | <0.01|
| Dryopteris       | 102  | 0.07| 78   | 0.03| 90   | 0.03|
| Matteuccia       | 15   | 0.01| 18   | 0.01| 22   | 0.01|
| Polypodium       | 2    | <0.01| 1    | <0.01| 4   | <0.01|
| Total            | 159  | 0.10| 155  | 0.07| 201  | 0.07|
| Microalgae       |      |     |      |     |      |     |
| Chlorophyta      | *    | *    | 24,342 | 10.52| 18,060 | 6.73|
| Invertebrates    |      |     |      |     |      |     |
| Thysanoptera     | 12   | 0.01| 8    | <0.01| 8   | <0.01|
Table 1 (continued)

| Taxa              | 2019 Σ | % | 2020 Σ | % | 2021 Σ | % |
|-------------------|--------|---|--------|---|--------|---|
| Hymenoptera       | 8.00   | 0.01 | 4.00   | <0.01 | 2.00   | <0.01 |
| Diptera           | 25.00  | 0.02 | 12.00  | 0.01  | 6.00   | <0.01 |
| Aranea            | 3.00   | <0.01 | 2.00   | <0.01 | 5.00   | <0.01 |
| Sternorrhyncha    | 2.00   | <0.01 | 2.00   | <0.01 | -      | -     |
| Acari             | 103.00 | 0.07 | 142.00 | 0.06  | 162.00 | 0.06  |
| Total             | 153.00 | 0.1 | 170.00 | 0.07  | 183.00 | 0.07  |

*Not in operation; Cup/Tax, Cupressaceae/Taxaceae

Fig. 1 Monthly variation in airborne concentration of different types of bioparticles (arboreal pollen, herbaceous pollen, fungal spores, fern spores, microalgae and invertebrates) in Bratislava, years 2019–2021
be a factor that can positively or negatively influence the concentration of bioparticles in the air, negatively associated with fungal spores and positively with microalgae. Sunshine was significantly and positively attributed with arboreal pollen, fungal and fern spores, while relationships between precipitation and pollen were negative. Among the atmospheric pollutants, NO₂ and CO showed a mixed effect on the concentrations of bioparticles, negatively associated with microalgae and two arboreal pollen types (Pinaceae and Fraxinus), whereas positively with several taxa of fungal spores, fern spores, herbaceous pollen at assemblage level and two arboreal pollen types (Betula and Populus). The airborne concentration of all types of bioparticles increased with the increasing concentration of PM₁₀ and O₃, except for microalgae, negatively associated with PM₁₀, and invertebrates without significant association with O₃.

Discussion

The airborne pollen/spore concentration does not always correlate well with symptoms of allergic rhinoconjunctivitis in sensitive individuals. Allergy sufferers may experience allergy symptoms even when the amount of the causative allergen in the ambient air is low (Moreno-Grau et al. 2006; Buters et al. 2015). It is partly due to the fact that data on the concentration of individual types of intact bioparticles in the air may not reflect the total exposure to aeroallergens.
because under specific meteorological conditions, they are fragmented, and allergenic molecules are released directly into the air (Taylor et al. 2002). Fine bioparticle fragments containing allergenic molecules enter the lower respiratory tract due to their small size (< 2 µm), either alone or with attached pollutants in the form of “complex particles”, and can cause severe allergic reactions in sensitive individuals (Taylor et al. 2004). In this context, there is some doubt about the concentration of intact bioparticles (e.g. pollen grains or fungal spores) as a reliable proxy for allergenic exposure. On the other hand, however, other aeroallergens may be behind the worsening of allergic symptoms in some patients. In the air of Bratislava, in addition to abundantly represented fungal spores and pollen grains, we also recorded other bioparticles with the potential to evoke respiratory allergic diseases, namely fern spores (Rodríguez de la Cruz et al. 2018; Ščevková et al. 2022), microalgae (Tesson et al. 2016; Wiśniewska et al. 2019) and invertebrates (Calderón et al. 2015; Wang et al. 2016). These bioparticles, which represented approximately 9% of the total annual concentration of all analysed bioparticles in the study area, would deserve more attention from aerobiologists.

Based on our results, it appears that bioparticles that may harm human health are present in the air throughout the year. In addition to arboreal pollen, from late winter to early spring, February–April, microalgae can also cause health problems in the study area. That arboreal pollen grains are among the momentous aeroallergens is confirmed by

Fig. 3 Monthly evaluation of meteorological variables (temperature and precipitation) and anthropogenic pollutants (ozone, PM10, CO and NO2) in the air of Bratislava, years 2019–2021
of invertebrates can also induce allergic respiratory disease. Pinaceae 

Tmean, relative humidity; WS, wind speed; O₃, ozone; PM₁₀, particulate matter ≤10 μm; PM₂.₅, particulate matter ≤2.₅ μm; CO, carbon monoxide; NO₂, nitrogen dioxide; Cup/Tax, Cupressaceae/Taxaceae; N, number of cases.

Table 3 Spearmann’s correlation coefficients between the mean daily concentrations of individual types of bioparticles and selected meteorological parameters and air pollutants, recorded in Bratislava over the years 2019–2021

| Variables          | N  | Tmean | S       | P       | RH      | WS      | O₃     | PM₁₀   | CO      | NO₂     |
|--------------------|----|-------|---------|---------|---------|---------|--------|--------|---------|---------|
| Arboral pollen     | 355| 0.278*** | 0.313*** | −0.258*** | −0.502*** | −0.005 | 0.386*** | 0.177*** | −0.072 | 0.041 |
| Betula             | 94 | 0.249*  | 0.338*** | −0.233*  | −0.478*** | −0.226* | 0.497*** | 0.324*** | 0.232*  | 0.227*  |
| Cup/Tax            | 138| 0.261*  | −0.105  | 0.055   | 0.063   | 0.249*  | −0.098  | −0.095 | 0.005   | 0.015   |
| Fraxinus           | 137| 0.18    | 0.208*  | −0.136  | −0.321*** | −0.155 | 0.128   | −0.015  | −0.38*** | −0.179  |
| Pinaceae           | 128| −0.1    | 0.039   | 0.004   | −0.13   | −0.115 | 0.244*  | −0.082  | −0.346*** | −0.246*  |
| Populus            | 143| 0.199   | 0.18    | −0.156  | −0.06   | −0.173 | 0.169   | 0.326*** | 0.221*  | 0.226*  |
| Quercus            | 151| 0.195   | 0.269*** | −0.049  | −0.093  | −0.029 | 0.303** | 0.189   | 0.152   | 0.13     |
| Herbaceous pollen  | 362| 0.226*** | 0.045   | −0.109** | −0.176*** | −0.062 | 0.184*** | 0.328*** | 0.214*** | 0.269*** |
| Ambrosia           | 139| 0.462*** | 0.201   | −0.042  | −0.213*  | −0.013 | 0.539*** | 0.424*** | 0.116   | 0.088   |
| Poaceae            | 247| 0.087   | 0.143   | −0.138  | −0.117  | −0.025 | 0.349** | 0.214*  | −0.011  | 0.012   |
| Urticaceae         | 394| 0.302** | −0.179  | −0.064  | 0.128   | 0.078  | −0.154  | 0.052   | 0.148   | 0.197   |
| Fungal spores      | 791| 0.772*** | 0.271*** | −0.072  | 0.192*** | −0.407*** | 0.208*** | 0.146** | 0.177*** | −0.089  |
| Alternaria         | 506| 0.241*  | 0.188   | −0.199  | −0.397*** | −0.094 | 0.148   | 0.156   | −0.174  | 0.244*  |
| Cladosporium       | 774| 0.547*** | 0.29**  | −0.179  | −0.054  | −0.195 | 0.317** | 0.16    | 0.066   | −0.082  |
| Epicoccum          | 471| 0.365*** | 0.116   | −0.166  | −0.272** | −0.056 | 0.111   | 0.186   | −0.041  | 0.31**  |
| Stiphephyllum      | 390| 0.358*** | 0.165   | −0.247* | −0.022  | −0.005 | 0.193   | 0.473*** | 0.264*  | 0.157   |
| Fern spores        | 333| 0.335*** | 0.237*** | −0.099  | −0.254*** | 0.022 | 0.371*** | 0.201*** | 0.136*  | −0.015  |
| Microalgae         | 546| −0.171** | 0.028   | −0.001  | −0.267*** | 0.194*** | 0.222**  | −0.2***  | −0.248*** | −0.182*** |
| Invertebrates      | 282| 0.216*  | 0.039   | −0.087  | −0.049  | −0.073 | 0.013   | 0.156*  | 0.006   | 0.012   |

*p < 0.05; **p < 0.01; ***p < 0.001; significant correlations are marked in bold.

multiple studies (e.g. D’Amato et al. 2007; Ribeiro et al. 2009). However, although aerosolized algae have received only marginal attention worldwide, these airborne bioparticles contain allergenic molecules, which are capable of inducing symptoms of respiratory allergic disease in sensitive individuals (Sharma et al. 2007; Genitsaris et al. 2011; Sahu and Tangutur 2014; Wiśniewska et al. 2019). Allergic diseases, such as rhinitis or contact dermatitis, can be induced by several genera of algae. However, the most important ones include Chlorella and Bracteacoccus attributed to phylum Chlorophyta (Genitsaris et al. 2011), commonly recovered from the atmospheric samples also in Bratislava. The most bioparticles in the air were observed in summer, June–August, with fungal spores and herbaceous pollen dominating. Other types of bioparticles such as fern spores and invertebrates were also detected during this period. Among fungal spores, “dry” spore types represented mainly by Cladosporium and Alternaria dominated. These spores, which are among the momentous fungal allergens (Fukutomi and Taniguchi 2015), are found abundantly in the air under conditions of increasing temperature and decreasing humidity (Elbert et al. 2007). Although their average daily concentration in the air did not exceed 15 spores or individuals per m³ of air, fern spores and mites of invertebrates can also induce allergic respiratory disease in susceptible individuals (de Blay et al. 1991; Burge and Rogers 2000).

Although air quality has improved in 2020 and 2021 due to the Covid-19 lockdowns, the concentrations of airborne bioparticles have increased compared to 2019. Contrary to our results, several researchers have found that as the levels of air pollutants increase, so does pollen production. For example, Ziska et al. (2003) and Rogers et al. (2006) reported that in urban locations where CO₂ concentrations are higher, Ambrosia plants produce more pollen than they do in rural areas. In general, however, the levels of air pollutants are low in Bratislava, only rarely exceeding the limit values (Závodský 2007). Even in 2019, when air pollution loads were higher than in the following 2 years, the air quality was satisfactory. It is due to Bratislava has good scattering conditions, which eliminates the accumulation of pollutants in the air (Závodský 2007). Hence, the higher levels of bioparticles in the air in 2020 and 2021 can be attributed to interannual fluctuations driven by climatic conditions rather than air quality improvement.

In addition to the biological characteristics of the parent organisms, the airborne levels of each type of bioparticle depend on meteorological factors, in particular temperature, relative humidity and wind speed. The increase in air temperature influenced the concentration of airborne
bioparticles positively, except for microalgae with a negative correlation. To be released from the source into the air or to become airborne, pollen grains, dry fungal spores and fern spores require a certain degree of dryness, which occurs when the air temperature increases (Kasprzyk et al. 2016). Although algae are present in the air throughout the year, their higher abundance is typical for spring or a period with lower average daily temperatures and higher wind speeds (Tormo et al. 2001). At the same time, air circulation is less dynamic during summer, when air temperatures reach their highest values, than in spring. And it was wind speed that significantly and positively correlated with the airborne microalgae concentration in the present study. Microalgae are mechanically segregated and aerosolized from their natural aquatic or terrestrial habitats by wind or water action and are subsequently transported by the air over various distances (Sharma and Singh 2010). An essential factor underlying aerosolization, especially from terrestrial sources, is dehydration of the substrate, where the algal surface becomes disturbed and individual cells and clumps are more easily detached and aerosolized (Sharma 2015). In contrast to microalgae, we observed a negative correlation between wind speed and most bioparticles, however, significant only for fungal spores. Although wind helps in bioparticles’ dispersal, it also promotes their dilution, probably resulting in this inverse relationship. Lin and Li (2000) pointed out that wind speeds of up to 5 m/s lead to dilution of the number of fungal spores in the air. And it is during summer, July–August, when fungal spores are abundant in the air, the wind speed is lowest, reaching an average daily value of 1.3 m/s.

The effect of relative humidity on the concentration of most airborne bioparticles, except for fungal spores at assemblage level, was negative. Reduction in the number of airborne bioparticles with increasing humidity has been observed by several researchers (e.g. Xu et al. 2012; Rahman et al. 2019; Uetake et al. 2019). The high humidity keeps the surface of the ground wet, and the bioparticles are attached to it due to the force of the surface tension. The bonding forces by which the bioparticles are annexed to the surface weaken with drying (Šantl-Temkiv et al. 2018). On the other hand, increased humidity positively affects fungal growth (Li and Kendrick 1995), which is reflected by increased amounts of spores in the air. Moreover, wet spores require humid conditions to activate the sporulation process (Almaguer-Chávez et al. 2018).

Urban air pollution poses serious environmental risks and health threats to city residents. It was shown that pollen allergic reactions are more severe when the concentration of particulate matter in the air is higher (Konishi et al. 2014). Although air pollutants, especially particulate matter, have been extensively studied and monitored in Bratislava due to their negative impact on public health, their bioparticle components remain unknown. In the present study, the concentration of most pollen types, fungal spores, fern spores and invertebrates was positively correlated with PM_{10} concentrations. It is worth noting the inorganic fraction of particulate matter could adhere to airborne bioparticles (Risse et al. 2000; Visez et al. 2020), which may disrupt the natural functions of their envelope and increase the bioavailability of allergens (Monn 2001). Moreover, particulate matter in the air can provide niches and act as energy sources and carriers for other airborne microorganisms, e.g. bacteria (Dong et al. 2016; Smets et al. 2016). Nevertheless, a significant negative association between PM_{10} and microalgae was observed in the present study. In this context, the interactions between different airborne bioparticles and the particulate matter should be further investigated.

The summer period was typical of elevated concentrations of tropospheric ozone, which were positively associated with the levels of most of the analysed types of airborne bioparticles. High ozone levels over the summer revealed that ozone formation is related to sunshine and air temperature (Sousa et al. 2008; Rahman et al. 2019). Temperature and sunlight directly influence the creation of tropospheric ozone by chemical reactions between oxides of nitrogen (NOx) and volatile organic compounds (VOC) (Steiner et al. 2010). High concentrations of tropospheric ozone in the air represent stress for some plants, resulting in increased production of stress hormones, some of them known as allergens (Eckl-Dorna et al. 2010), or increased release of cytoplasmic granules containing allergens from pollen grains into the air (Motta et al. 2006). In this context, the simultaneous increment in the airborne concentration of bioparticles and ozone may exacerbate the manifestations of allergic respiratory diseases in urban areas.

The correlation between different bioparticles and gaseous pollutants such as CO and NO_{2} was not statistically consistent and varied with positive–negative values. Contrary to other researchers (Roy and Bhattacharya 2020), who observed an adverse effect of CO and NO_{2} on airborne fungal ascospore concentration, the strong positive effect between CO and fungal spores at the assemblage level was observed in the present study. We also observed a positive effect of the above pollutants on the pollen of arboreal plants blooming in spring (Betula and Populus) or herbs blooming in autumn, when there is a higher concentration of gaseous pollutants in the air. According to Lighthart (1973), increased air humidity and the presence of gaseous pollutants can promote the growth of bacteria. Similarly, these chemical pollutants could stimulate the growth of some fungi, but thorough research would be needed in this regard. On the other hand, several studies (Mansfield et al. 1991; Korzun et al. 2008; Savi and Scussel 2014) point to a fungicidal effect of gaseous pollutants, with the concentration of the chemical for a given taxon being important. Similarly,
higher concentrations of airborne chemicals may inhibit microalgae growth since we observed a negative effect of CO and NO₂ on the concentration of these microorganisms in the air. However, further investigation should be carried out in this area.

**Conclusions**

We recorded 48 types of bioparticles in the air of Bratislava during the three analysed years, besides pollen and fungal spores, which were most abundant, including microalgae, fern spores and invertebrates.

In 2020 and 2021, although colder and more humid, with better air quality compared to 2019, we observed enhanced airborne concentrations of all types of bioparticles considered, probably attributed to interannual fluctuations driven by climatic conditions.

Based on the results of correlation analysis, individual types of bioparticles showed different sensitivities to the meteorological and air pollution factors. The air temperature was positively associated with most analysed bioparticles, while the association with relative humidity was negative. Except for microalgae and a few types of arboreal pollen, the airborne concentration of which decreased, with increasing values of CO, NO₂ and/or PM₁₀, the levels of other bioparticles increased with rising concentration of all air pollutants considered. It is important to note that inorganic air pollutants may interact with airborne bioparticles and increase their allergenic potential, posing a greater risk to allergy sufferers. Based on these results, we recommend investigating the response of pollen and fungal spores to environmental factors at the taxon level in future studies, as each taxon has a different pattern of development, probably attributed to interannual fluctuations driven by climatic conditions. The current findings of this study could help to improve the understanding of complex interactions between different types of airborne bioparticles, meteorological variables and air pollutants and contribute to manage seasonal respiratory allergic diseases in the central European region.

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**Author contribution** Jana Ščevková: conceptualization, formal analysis, methodology, supervision, validation, visualization, writing—original draft, writing—review and editing. Zuzana Vašková: investigation, visualization, writing—review and editing. Jozef Dušička: data curation, formal analysis, validation, visualization, writing—review and editing. Matuš Žilka: data curation, investigation, writing—review and editing. Martina Zvaríková: data curation, investigation, writing—review and editing.

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**References**

Almaguer-Chávez M, Aira MJ, Rojas TI, Fernández-González M, Rodríguez-Rajo FJ (2018) New findings of airborne fungal spores in the atmosphere of Havana, Cuba, using aerobiological non-viable methodology. Ann Agric Environ Med 25:349–359. https://doi.org/10.26444/aaem/89738

Azzazy M (2016) Environmental impacts of industrial pollution on pollen morphology of *Eucalyptus globulus* Labil. (Myrtaceae). App Biol Biotech 4:57–62. https://doi.org/10.7324/JABB.2016.40509

Burge HA, Rogers CA (2000) Outdoor allergens. Environ Health. Prospect 108:653–659. https://doi.org/10.1289/ehp.00108s4653

Buters JTM, Prank M, Sofiev M, Pusch G, Albertíni R, Annesi-Maesano I et al (2015) Variation of the group 5 grass pollen allergen content of airborne pollen in relation to geographic location and time in season the HIALINE working group. J Allergy Clin Immunol 136:87–95. https://doi.org/10.1016/j.jaci.2015.01.049

Calderón MA, Kleine-Tebbe J, Linneberg A, De Blay F, Fernandez de Rojas DH, Virchow JCh, Demoly P (2015) House dust mite respiratory allergy: an overview of current therapeutic strategies. J Allergy Clin Immunol Pract 3:843–855. https://doi.org/10.1016/j.jaip.2015.06.019

Cecchi L, D’Amato G, Ayres JG, Galan C, Forastiere F, Forsberg B et al (2010) Projections of the effects of climate change on allergic asthma: the contribution of aerobiology. Allergy 65:1073–1081. https://doi.org/10.1111/j.1398-9995.2010.02423.x

D’Amato G, Cecchi L, Bonini S, Nunes C, Annesi-Maesano I, Behrendt H, Liccardi G, Popov T, van Cauwenberge P (2007) Allergic pollen and pollen allergy in Europe. Allergy 62:976–990. https://doi.org/10.1111/j.1398-9995.2007.01393.x

D’Amato G, Cecchi L, D’Amato M, Liccardi G (2010) Urban air pollution and climate change as environmental risk factors of respiratory allergy: an update. J Investig Allergol Clin Immunol 20:95–102 de Blay F, Heymann PW, Chapman MD, Platts-Mills TAE (1991) Airborne dust mite allergens: comparison of group II allergens with group I mite allergen and cat-allergen Fel d 1. J J Allergy Clin Immunol 88:919–926. https://doi.org/10.1016/j.jaci.2015.04.009

Després VR, Huffman JA, Burrows SM, Hooce C, Safatov AS, Buryak G et al (2012) Primary biological aerosol particles in the atmosphere: a review. Tellus B 64:15598. https://doi.org/10.3402/tellusb.v64i0.15598

Dong L, Qi J, Shao C, Zhong X, Gao D, Cao W, Gao J, Bai R, Long G, Chu C (2016) Concentration and size distribution of total airborne microbes in hazy and foggy weather. Sci Total Environ 541:1011–1018. https://doi.org/10.1016/j.scitotenv.2015.10.001

Eckl-Dorna J, Klein B, Reichenauer TG, Niederberger V, Valenta R (2010) Exposure of rye (*Secale cereale*) cultivars to elevated ozone levels increases the allergen content in pollen. J Allergy Clin Immunol 126:1315–1317. https://doi.org/10.1016/j.jaci.2010.06.012
Elbert W, Taylor PE, Andreae MO, Pöschl U (2007) Contributions of fungi to primary biogenic aerosols in the atmosphere: wet and dry discharged spores, carbohydrates, and inorganic ions. Atmos Chem Phys 7:4569–4588. https://doi.org/10.5194/acp-7-4569-2007

Feráková V, Jarolímek I (2011) Bratislava. In: Kelcey JG, Müller N (eds) Plants and habitats of European cities. Springer

Fukutomii Y, Taniguchi M (2015) Sensitization to fungal allergens: resolved and unresolved issues. Allergol Int 64:321–331. https://doi.org/10.1016/j.alit.2015.05.007

Galán C, Cariñanos P, Alcázar P, Domínguez-Vilches E (2007) Spanish aerobiology network (REA): Management and quality manual. Servicio de publicaciones de la Universidad de Córdoba, Córdoba

Galán C, Smith M, Thibaudon M, Frenguelli G, Oteros J, Gehrig R et al (2014) Pollen monitoring: minimum requirements and reproducibility of analysis. Aerobiologia 30:385–395. https://doi.org/10.1007/s10453-014-9335-5

Genitsaris S, Kormas KA, Moustaka-Gouni M (2011) Airborne algae and cyanobacteria: occurrence and related health effects. Front Microbiol 3:772–787. http://doi.org/10.3389/fmicb.2012.00246.x

Grant Smith E (2000) Sampling and identifying allergenic pollens and moulds. Bluestone Press, San Antonio, TX

Grewing E, Fratczak A, Kosteki L, Nowak M, Szymańska A, Bogowski P (2019) Biological and chemical air pollutants in an urban area of Central Europe: Co-exposure assessment. Aerosol Air Qual Res 19:1526–1537. https://doi.org/10.4209/aapr.2018.10.0365

Grinn-Grofroñ A, Strzelczak A, Wolski T (2011) The relationships between air pollutants, meteorological parameters and concentration of airborne fungal spores. Environ Polut 159:602–608. https://doi.org/10.1016/j.envpol.2010.10.002

Hirst JM (1952) An automatic volumetric spore trap. Ann Appl Biol 39:257–265. https://doi.org/10.1111/j.1744-7348.1952.tb00904.x

Hofbauer WK, Gärssen JW, Hall J, Sauer R (2008) The effect of ozone on common allergens Olea europaea and Paritiera judaica pollen counts and quantification of their major allergens Ole e 1 and Par j 1-Par j 2. Ann Allergy Asthma Immunol 96:858–864. https://doi.org/10.1016/S1081-3519(08)00030-7

Morten-Grav S, Elvira-Rendueles B, Moreno J, Garcia-Sanchez A, Vergara N, Asturias JA, Arilla MC, Ibarrloa I, Seoane-Camba JA, Suarez-Cervera M (2006) Correlation between Olea europaea and Paritiera judaica pollen counts and quantification of their major allergens Ole e 1 and Par j 1-Par j 2. Ann Allergy Asthma Immunol 96:858–864. https://doi.org/10.1016/S1081-3519(08)00030-7

Mota AC, Marliere M, Peltre G, Sterenberg P, Lacroix G (2006) Traffic-related air pollutants induce the release of allergen-containing cytoplasmic granules from grass pollen. Int Arch Allergy Immunol 139:294–298. https://doi.org/10.1159/000091600

Puc M (2011) Threat of allergenic airborne grass pollen in Szczecin, NW Poland: the dynamics of pollen seasons, effect of meteorological variables and air pollution. Aerobiologia 27:191–202. https://doi.org/10.1007/s10453-010-9188-5

Puc M, Bosiacka B (2011) Effects of meteorological factors and air pollution on pollen concentrations. Pol J Environ Stud 20:611–618

Rahman A, Luo Ch, Khan MHR, Ke J, Thilakanayaka V, Kumar S (2019) Influence of atmospheric PM2.5, PM10, O3, CO, NO2, SO2, and meteorological factors on the concentration of airborne pollen in Guangzhou. China Atmos Environ 129:290–304. https://doi.org/10.1016/j.scitotenv.2019.05.049

Rai PK (2016) Impacts of particulate matter pollution on plants: implications for environmental biomonitoring. Ecotoxicol Environ Saf 129:120–136. https://doi.org/10.1016/j.ecoenv.2016.03.012

Reynolds DR, Reynolds AM, Chapman JW (2014) Non-volatile modes of migration in terrestrial arthropods. Anim Mov 2:8–28. https://doi.org/10.2478/amv-2014-0002

Ribeiro H, Oliveira M, Ribeiro N, Cruz A, Ferreira A, Machado H, Reis A, Abreu I (2009) Pollen allergenic potential nature of some trees species: a multidisciplinary approach using aerobiological, immunological, and chemical data. Environ Res 90:328–333. https://doi.org/10.1016/j.envres.2008.11.008

Ribeiro H, Costa C, Abreu I, Esteves da Silva JCG (2017) Effect of O3 and NO2 atmospheric pollutants on Platanus x acerifolia pollen: Immunological and spectroscopic analysis. Sci Total Environ 599–600:291–297. https://doi.org/10.1016/j.scitotenv.2017.04.206

Risse U, Tomczok J, Huss-Marpl J, Darsow U, Behrendt H (2000) Health-relevant interaction between airborne particulate matter and aeroallergens (pollen). J Aerosol Sci 31:27–28. https://doi.org/10.1016/S0021-8502(00)00033-8

Rodríguez de la Cruz DR, Sánchez-Reyes E, Sánchez-Sánchez J, Sánchez-Agudo JÁ (2018) New insights on atmospheric fern spore dynamics. In: Fernández H (ed) Current Advances in Fern Research. Springer, Switzerland, pp 427–452

Rogers CH, Wayne PM, Macklin EA, Muilenberg ML, Wagner CH, Epstein PR, Bazzaz FA (2006) Interaction of the onset of...
spring and elevated atmospheric CO₂ on ragweed (Ambrosia artemisiifolia L.) pollen production. Environ Health Perspect 114:865–869. https://doi.org/10.1289/ehp.8549
Roy S, Bhattacharya SG (2020) Airborne fungal spore concentration in an industrial township: distribution and relation with meteorological parameters. Aerobiologia 36:575–587. https://doi.org/10.1007/s10453-020-09653-9
Sahu N, Tangtur AD (2014) Airborne algae: overview of the current status and its implications on the environment. Aerobiologia 31:89–97. https://doi.org/10.1007/s10453-014-9349-z
Ščetina X, Gosewinkel U, Starnawski P, Lever M, Finster K (2018) Aeolian dispersal of bacteria in Southwest Greenland: their sources, abundance and diversity and physiological states. FEMS Microbiol Ecol 94:1–10. https://doi.org/10.1093/femsec/fiy031
Savi GD, Scussell VM (2014) Effects of ozone gas exposure on toxicogenic fungi species from Fusarium, Aspergillus, and Penicillium genera. Ozone: Sci Eng 36:144–152. https://doi.org/10.1080/01919512.2013.846824
Ščeková J, Kovač J (2019) First fungal spore calendar for the atmosphere of Bratislava, Slovakia. Aerobiologia 35:343–356. https://doi.org/10.1007/s10453-019-09564-4
Ščeková J, Vášková Z, Sepešová R, Dušička J, Kovač J (2020) Relationship between Poaceae pollen and PH₅ pollergen concentrations and the impact of weather variables and air pollutants on their levels in the atmosphere. HELIYON 6:e06421. https://doi.org/10.1016/j.heliyon.2020.e06421
Ščeková J, Vášková Z, Dušička J, Hrabovský M (2022) Fern spores: neglected airborne bioparticles threatening human health in urban environments. Urban Ecosystems (in Press). https://doi.org/10.1007/s11252-022-01263-2
Sharma NK (2015) Airborne algae: their significance. Nova Science Publishers, New York Inc., p 103
Sharma NK, Singh S (2010) Differential aerosolization mediated by climatic factors regulates abundance of algal particles in the atmosphere. Ind Microbiol 50:468–473. https://doi.org/10.1007/s12088-011-0146-x
Sharma NK, Rai AK, Singh S, Brown RM (2007) Airborne algae: present status and their relevance. J Phycol 43:615–627. https://doi.org/10.1111/j.1529-8817.2007.00373.x
Smets W, Moretti S, Denys S, Lebeer S (2016) Airborne bacteria in the atmosphere: presence, purpose, and potential. Atmos Environ 139:214–221. https://doi.org/10.1016/j.atmosenv.2016.05.038
Souza SIV, Martins FG, Pereira MC, Alvim-Ferraz MCM, Ribeiro H, Oliveira M, Albreu J (2008) Influence of atmospheric ozone, PM₄, and meteorological factors on the concentration of airborne pollen and fungal spores. Atmos Environ 42:7452–7464. https://doi.org/10.1016/j.atmosenv.2008.06.004
Steiner AL, Davis AJ, Sillman S, Owen RC, Michalak AM, Fiore AM (2010) Observed suppression of ozone formation at extremely high temperatures due to chemical and biophysical feedbacks. PNAS 107(46):19685–19690. https://doi.org/10.1073/pnas.1008336107
Suárez-Cervera M, Castells T, Vega-Maray A, Civantos E, del Pozo V, Fernández-González D et al (2008) Effects of air pollution on Cup 3 allergen in Cupressus arizonica pollen grains. Ann Allergy Asthma Immunol 101:57–66. https://doi.org/10.1016/S1051-2106(10)80386-8
Taketomi EA, Sopelete MC, Moreira PFDS, Vieira FDAM (2006) Pollen allergic disease; pollens and its major allergens. Revista Brasileira De Otorrinolaringologia 72:562–567. https://doi.org/10.1016/S1808-8694(15)31005-3
Taylor PE, Flagan RC, Valenta R, Glovyks MM (2002) Release of allergens as respirable aerosols: a link between grass pollen and asthma. J Allergy Clin Immunol 109:51–56. https://doi.org/10.1067/mai.2002.120759
Taylor PE, Flagan RC, Miguel AG, Valenta R, Glovyks MM (2004) Birch pollen rupture and the release of aerosols of respirable allergens. Clin Exp Allergy 34:1591–1596. https://doi.org/10.1111/j.1365-2222.2004.02078.x
Tesson SVM, Skjøth CA, Šantl-Temkiv T, Lündahl J (2016) Airborne microalgae: insights, opportunities, and challenges. Appl Environ Microbiol 82:1978–1991. https://doi.org/10.1128/AEM.03333-15
Tormo R, Riccio D, Silva I, Muñoz AF (2001) A quantitative investigation of airborne algae and lichen soredia obtained from pollen trap in South-west Spain. Eur J Phycol 36:385–390. https://doi.org/10.1080/0967026011001735538
Torres P, Ferreira J, Monteiro A, Costa S, Pereira MC, Madureira J, Mendes A, Teixeira JP (2018) Air pollution: a public health approach for Portugal. Sci Total Environ 643:1041–1053. https://doi.org/10.1016/j.scitotenv.2018.06.2810048-9697
Uetake J, Tobe Y, Uji Y, Hill TCI, DeMott P, Kreidenweis SM, Misumi R (2019) Seasonal changes of airborne bacterial communities over Tokyo and influence of local meteorology. Front Microbiol 10:e1572. https://doi.org/10.3389/fmicb.2019.01572
Víseček N, Ivanovsky A, Roose A, Gosselin S, Sénéchal H, Poncet P, Choël M (2020) Atmospheric particulate matter adhesion onto pollen: a review. Aerobiologia 36:49–62. https://doi.org/10.1080/01401239.2019.1673362
Wang I-J, Tung T-H, Tang C-S, Zhao Z-H (2016) Allergens, air pollutants, and childhood allergic diseases. Int J Hyg Environ Health 219:66–71. https://doi.org/10.1016/j.ijheh.2015.09.001
Willeke K, Machcr JM (1999) Air sampling. In: Machcr JM (ed) Bioaerosols assessment and control. ACCHI, Cincinnati, OH
Wiśniewska K, Lewandowska AL, Sliwińska-Wilczewska S (2019) The importance of cyanobacteria and microalgae present in aerosols to human health and the environment –Review study. Environ Int 131:e104964. https://doi.org/10.1016/j.envint.2019.104964
Xu JX, Zhang DS, Li LH (2012) Seasonal variations of airborne pollen in Beijing, China and their relationships with meteorological factors. Acta Ecol Sin 32:202–208. https://doi.org/10.1016/j.chinaes.2012.05.002
Xue Y, Chu J, Li Y, Kong X (2020) The influence of air pollution on respiratory microbiome: a link to respiratory disease. Toxicol Lett 334:14–20. https://doi.org/10.1016/j.toxlet.2020.09.007
Závodský D (2007) Air pollution in Bratislava, 1965-2005. In: Strelcová K, Skvarenina J and Blázenec M (eds) Bioclimatology and natural hazards. International Scientific Conference, Poľana nad Detvou, Slovakia, September 17–20, 2007
Zenkteler E (2012) Morphology and peculiar features of spores of fern species occurring in Poland. Acta Agrobot 65:3–10. https://doi.org/10.5586/AA.2012.053
Ziemianin M, Waga J, Czarnobilska E, Myszkowska D (2021) Changes in qualitative and quantitative traits of birch (Betula pendula) pollen allergenic proteins in relation to the pollution status and its implications on the environment. Aerobiologia 37:89–97. https://doi.org/10.1007/s10453-019-09616-9
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