

Environmental factors associated with variation in airborne pollen concentrations revealed by automated aerobiological measurements

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Abstract

The impact of meteorological factors and air pollution on the dynamics of allergenic pollen dispersal was investigated in this study using automated monitoring data. In 2022-2024, pollen concentration data for *Alnus*, *Betula*, *Corylus*, and Poaceae collected in Vilnius (Lithuania) using an automated bioaerosol measurement device were applied to analyse not only pollen seasonality (start, end, and length) but also correlations with meteorological variables and air pollution. A 40-day pre-season window was used to investigate the effects of pre-season meteorological conditions on changes in pollen concentration and seasonality. The study revealed that the Betulaceae family (including *Alnus*, *Betula*, *Corylus*) pollen season started earlier than the Poaceae family, but was shorter (82 days on average), while the Poaceae family had the longest season (93 days on average). Pollen concentrations increased between 2022 and 2024. The study found statistically significant positive correlations linking air temperature and hourly pollen concentrations (*Betula*: $r = 0.39$ to 0.62 , $p < 0.01$; weaker with other pollen types) and negative correlations with relative air humidity (*Betula*: $r = -0.47$ to -0.67 , $p < 0.01$; weaker with other pollen types), while the effect of precipitation, wind direction and wind speed was mostly statistically weak. With respect to *Betula* and *Corylus*, pre-season meteorological conditions with higher air temperatures and lower relative humidity were associated with higher pollen concentrations, and for *Corylus* and Poaceae, they were associated with a longer season. Air pollution analysis revealed that pollen concentrations were more often positively correlated with PM, NO_x and CO, but these relationships were not unidirectional and depended on plant taxa. This study enables automated pollen monitoring data to reveal relevant aspects of the statistical analysis of meteorological parameters and air pollution, as well as the dynamics of airborne pollen concentration.

Keywords: aerobiology; air pollution; Lithuania; meteorological factors; pollen concentration

Introduction

The observation of airborne pollen has changed rapidly in recent years due to the increasing use of devices capable of automatically identifying biological particles, especially pollen (Tummon *et al.*, 2024). These devices generate high-temporal-resolution data, enabling a more detailed assessment of airborne pollen

Received: 11 Feb 2026. Received in revised form: 24 Mar 2026. Accepted: 24 Mar 2026. Published online: 30 Mar 2026.

From Volume 49, Issue 1, 2021, Notulae Botanicae Horti Agrobotanici Cluj-Napoca journal uses article numbers in place of the traditional method of continuous pagination through the volume. The journal will continue to appear quarterly, as before, with four annual numbers.

concentration dynamics than traditional measurements with Hirst-type or other manual devices (Maya-Manzano *et al.*, 2023). This creates a need to reassess the relationship between environmental factors and changes in pollen concentrations, especially in daily variations.

The transport of pollen from anemophilous plants is determined by weather conditions and factors that influence them, such as wind direction and speed, air temperature, relative humidity, and precipitation (Zemmer *et al.*, 2022; Subba *et al.*, 2023; Chico-Fernández and Ayuga-Téllez, 2025). Air quality also plays an important role in pollen dispersion. Airborne pollen concentrations may be linked to changes in air pollution and to meteorological conditions (Oduber *et al.*, 2019; Šaulienė *et al.*, 2019). It has been found that PM (particulate matter) negatively affects pollen, i.e., it can alter pollen morphology and structure (Oduber *et al.*, 2019; Bishan *et al.*, 2020). The combination of air pollution and pollen is harmful to people sensitive to pollen, as both airborne pollen and air pollutants are associated with respiratory diseases (Oduber *et al.*, 2019; Ravindra *et al.*, 2022). Therefore, scientific evidence on the relationships among pollen concentration, meteorological conditions and air quality is important, especially in densely populated urban or industrial areas.

Daily weather conditions are constantly changing atmospheric phenomena that influence fluctuations in pollen dispersal, while climatic conditions determine plant distribution and the length of the growing season. Climate change is shifting the growing season. For example, a study in Lithuania showed an earlier start of the growing season and plant flowering (Veriankaitė *et al.*, 2010b; Romanovskaja and Bakšienė, 2020). The shift in the start of the growing season has also been documented in other European countries, including Poland (Szyga-Pluta *et al.*, 2023) and Finland, where the growing season of crops shifted from 1996 to 2016, advancing to an earlier onset (Peltonen-Sainio and Jauhiainen, 2020). An advanced growing season has also been observed in the European Alps (Vitasse *et al.*, 2021). Consequently, climate change is causing the growing season to start earlier, and these changes are also affecting pollen season patterns.

Aerobiological information has been increasingly disseminated in recent years through digital solutions and mobile applications (e.g., PASYFO and MASK-air), which integrate pollen forecasts, symptom monitoring, and risk assessment, and may allow personalisation (Zapata *et al.*, 2024). As public awareness of airborne pollen dispersal increases, there is a need for timely, personalised aerobiological information. However, significant challenges remain in this context: compared to meteorological data, aerobiological information is less accessible to society, and there is a lack of more accurate, locally tailored forecasting systems. Additionally, it is important to assess the potential impact of meteorological factors and air pollution before the start of the pollen season to improve the prediction of risks associated with pollen. The efficiency of spreading information about bioaerosols is determined directly by the precision of forecasting models (Sofiev, 2019), which, until now, have mostly relied on input data collected with manual traps.

The introduction of automated pollen observation has enabled the collection of large amounts of high-resolution data, allowing detailed recording of fluctuations in pollen concentrations. This provides a basis for reassessing the dependence of airborne pollen concentrations on meteorological and air quality variables, allowing a more reliable application of the identified correlations in allergenic pollen risk forecasting models and in broader air quality decisions involving bioaerosols. This study enables automated pollen monitoring data to reveal relevant aspects of the statistical analysis of meteorological parameters and air pollution, as well as the dynamics of airborne pollen concentration. The results provide new insights into more accurately assessing the risks associated with pollen exposure and can be used to improve modelling.

Materials and Methods

Airborne pollen data

This study uses pollen concentration data collected in Vilnius (Lithuania) between 2022 and 2024. The data were obtained using the SwisensPoleno Mars automatic bioaerosol measurement device, which operates

on a holographic principle and can identify airborne pollen in near-real time (Swisens, 2023). Pollen data were obtained using manufacturer identification algorithms valid in 2024. The device is situated on the roof of Vilnius University Life Sciences Center (54.722032, 25.325993), which is located in an urban area, surrounded by busy streets, residential areas and greenery. The study analysed two time series of data – hourly and daily – on the concentrations of alder (*Alnus*), birch (*Betula*), hazel (*Corylus*), and grass (Poaceae) pollen. Missing pollen data were excluded from the evaluation (case analysis) to avoid additional potential errors in relation to the data. Daily pollen concentrations were used to assess the distribution of data (total, average and maximum values) and to determine the start and end of pollen seasons. The threshold concentration value was calculated based on the cumulative sum of daily concentrations, and the start and end of the season were defined as the dates when the cumulative total reached 2.5% and 97.5% of the annual sum (Nilsson and Persson, 1981; Andersen, 1991). This criterion may help limit the influence of occasional events, such as long-distance pollen transport, and has been used in previous aerobiological studies conducted in Lithuania (Veriankaitė *et al.*, 2010a; Šaulienė *et al.*, 2019). The Seasonal Pollen Index (SPI) was also evaluated, which indicates the sum of pollen concentrations throughout the pollen season for a single pollen type (Murray *et al.*, 2016; Sofiev, 2017).

Hourly pollen concentration data were used and analysed, together with hourly meteorological data, to evaluate the association between pollen concentrations and meteorological factors, while average daily pollen concentrations were used to analyse links with air pollutants. Average values were documented 40 days before the start of the pollen season (pre-season window) and used to compare possible relationships across different periods. During the pre-season window, daily pollen concentrations were associated with indicators of average air temperature and relative humidity, as well as key air pollution parameters. This pre-season window was chosen based on literature indicating that meteorological factors in the 30 days before the pollen season of Poaceae may be associated with pollen occurrence (Myszkowska, 2014a). The 40-day period is designed to approximately cover the minimum pre-season interval reported in previous studies and to allow the assessment of possible pre-season effects of meteorological factors and pollutants.

Meteorological and air quality data

Meteorological parameters were selected based on previous studies on the relationships between pollen concentrations and environmental factors. Air temperature (°C), precipitation (mm), wind speed (m/s), wind direction (°), and relative humidity (%) were analysed. The available meteorological data resolution was hourly. Hourly meteorological data for 2022-2024 were obtained from the Vilnius University meteorological station and the Lithuanian Hydrometeorological Service under the Ministry of Environment (LHMT).

Air pollution data for 2022-2024, including PM_{2.5} (µg/m³), PM₁₀ (µg/m³), CO (mg/m³), NH₃ (µg/m³), NO₂ (µg/m³), NO (µg/m³), O₃ (µg/m³), and SO₂ (µg/m³) concentrations, were taken from the Vilnius City Municipality's open access data platform. The available air pollution data were at the daily resolution. Air quality data were analysed by using case analysis, in which missing values were excluded. This method was selected to avoid additional potential errors in relation to the data. The study used daily air pollution data from two areas: one at 54.701992, 25.310047, which is 2,49 km from the pollen observation site, and another at 54.684902, 25.30619, which is 4,35 km away. Two locations were selected based on data availability: in the first location, only data for PM_{2.5} and PM₁₀ were available; in the second location, a wider range of pollutants (CO, NH₃, NO₂, NO, O₃, and SO₂) was available. The chosen areas closely match the site's landscape and vegetation characteristics, as airborne pollen concentration data were collected at both locations, which are situated in an urban environment characterised by nearby busy streets, residential zones, and vegetation-rich areas.

Statistical data analysis

Pollen concentration data for 2022-2024 were analysed on an hourly and daily resolution. Statistical analysis was performed using the "PAST 4.03" program (Hammer *et al.*, 2001). Based on daily indicators, standard deviation and maximum pollen concentration were calculated for each plant genus/family studied. The assumption of normality was assessed using the Shapiro-Wilk and Anderson-Darling tests for both hourly and daily pollen data. As the pollen data did not meet the assumption of normality, nonparametric methods were used in the statistical analysis. Statistical comparison between hourly pollen concentrations and meteorological factors, as well as between daily pollen concentrations and air pollution were made using Spearman's rank correlation coefficients. The statistical significance of the correlation coefficients was evaluated using a $p < 0.05$ as the significance threshold. A box-and-whisker plot was used to assess air pollution dynamics 40 days before the start of the season and to analyse the SPI. Mean pollen season timing was based on mean daily pollen concentrations, while the box-and-whisker plot illustrates the distribution of the data. Plots of mean meteorological and air quality data were based on daily value calculations for a particular year.

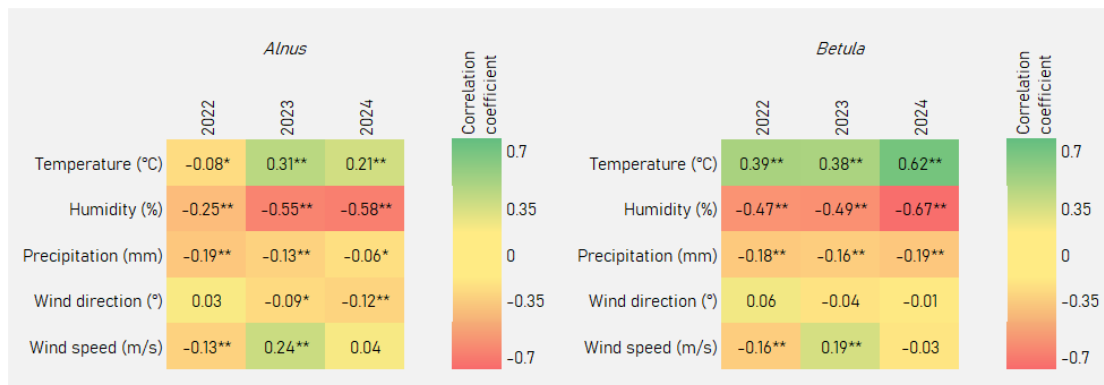
Results

Pollen concentration dynamics

Data obtained by the SwisensPoleno Mars automatic bioaerosol measurement device at Vilnius was used to analyse *Alnus*, *Betula*, *Corylus*, and Poaceae airborne pollen. Evaluation of 2022-2024 airborne pollen data showed that in the urban environment, *Alnus* and *Corylus* pollen were detected from February to March. The pollen season for Poaceae was the longest (93 days) compared to *Alnus* (44 days on average), *Betula* (45 days on average) and *Corylus* (36 days on average). When analysing the Betulaceae family (including *Alnus*, *Betula*, *Corylus*) as a whole, the pollen season lasted an average of 82 days. An evaluation of total pollen concentrations showed that the highest concentrations were detected for *Betula* pollen (e.g., in 2023 - up to 11,788 pollen/m³), and the lowest for *Corylus* (in 2023 - 71 pollen/m³).

Links between pollen concentration in the air and meteorological conditions

Evaluation of environmental factors that may influence pollen dispersal requires an assessment of meteorological conditions during the study period. For this purpose, a statistical relationship between meteorological parameters and airborne pollen concentration was analysed (Figure 1).



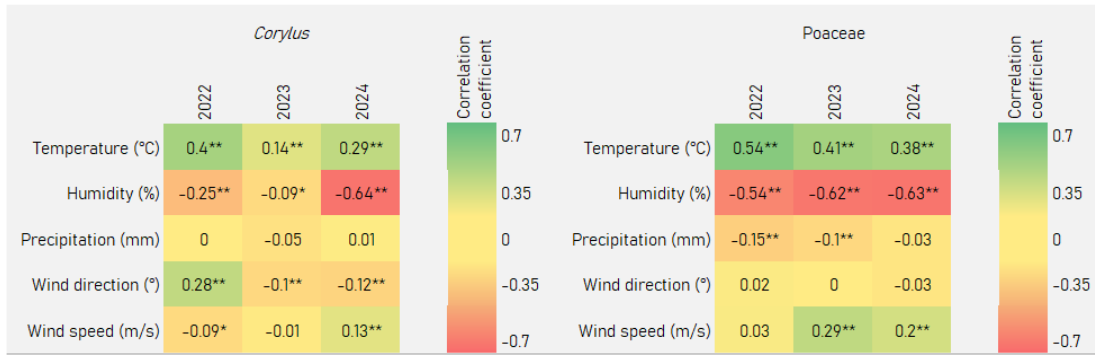
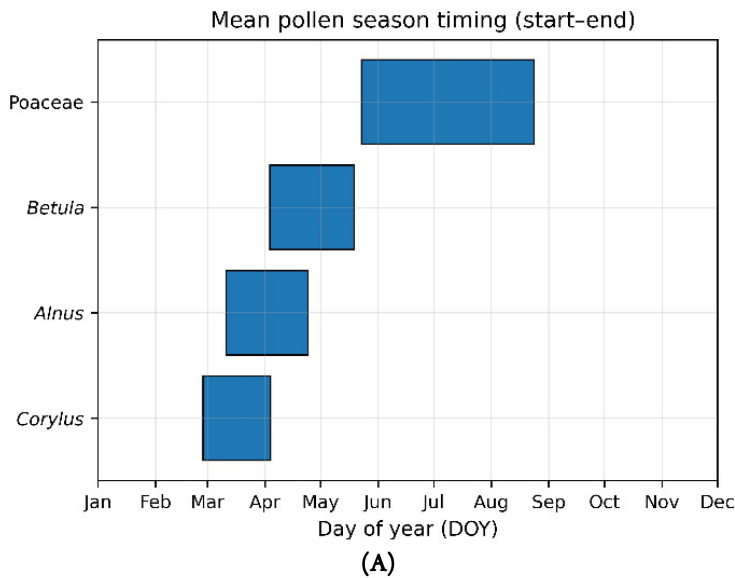
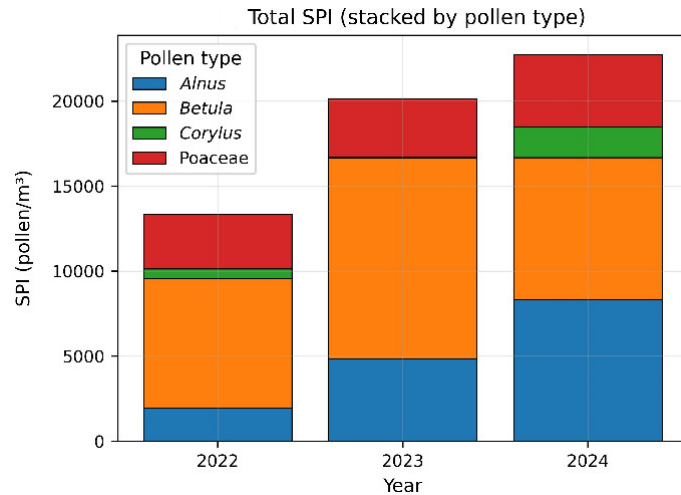


Figure 1. Statistical associations between hourly pollen concentrations of *Alnus*, *Betula*, *Corylus*, *Poaceae* and meteorological factors in 2022-2024 (* $p < 0.05$, ** $p < 0.01$)

The highest correlation coefficients were found between hourly pollen concentrations and air temperature (e.g., *Betula*: $r = 0.62$, $p < 0.01$) and relative humidity (e.g., *Betula*: $r = -0.67$, $p < 0.01$; *Corylus*: $r = -0.64$, $p < 0.01$). Correlations with precipitation were weak in most cases; correlation coefficients were mostly negative and, in some cases, statistically significant. When assessing correlations with wind direction, most were statistically insignificant, except for a positive relationship with *Corylus* pollen concentrations in 2022. The links between pollen concentration and wind speed resulted in comparatively low correlation coefficients.

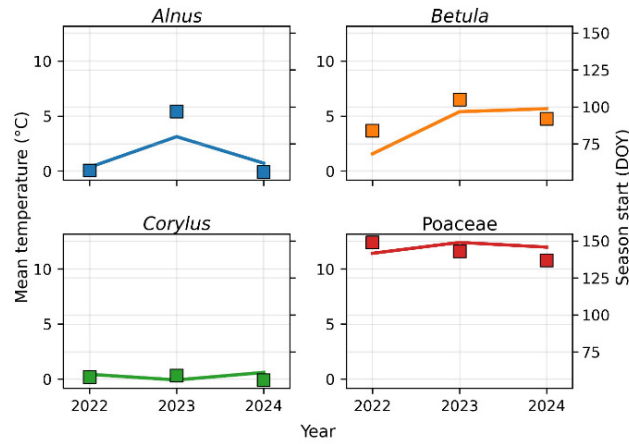
Considering that not only fluctuations in airborne pollen concentration can be influenced by meteorological variables, but also the start and intensity of the pollen season can be identified, conditions prior to the pollen season were additionally evaluated using a 40-day pre-season window (40 days before the pollen season start). The results of this analysis are presented in Figure 2.





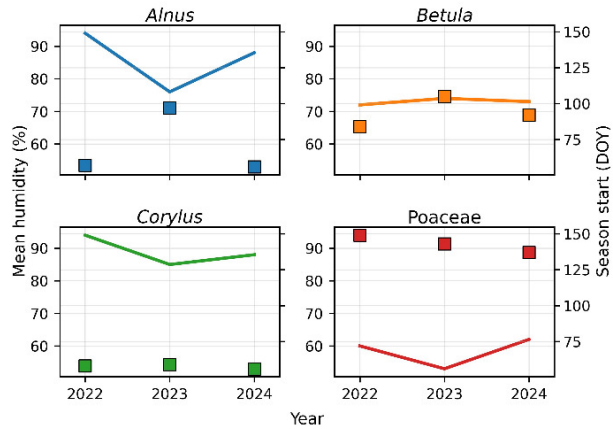
(B)

Temperature (line) and season start (squares) — per pollen type



(C)

Humidity (line) and season start (squares) — per pollen type



(D)

Figure 2. Mean pollen season, Seasonal Pollen Index (SPI) variation related to pollen season and pre-season meteorological condition: (A) Mean pollen season duration (in DOY – day of year), (B) SPI (pollen/m³), (C) air temperature (°C) and (D) relative humidity (%) 40 days in pre-season window with relation to the start of the pollen season (2022-2024)

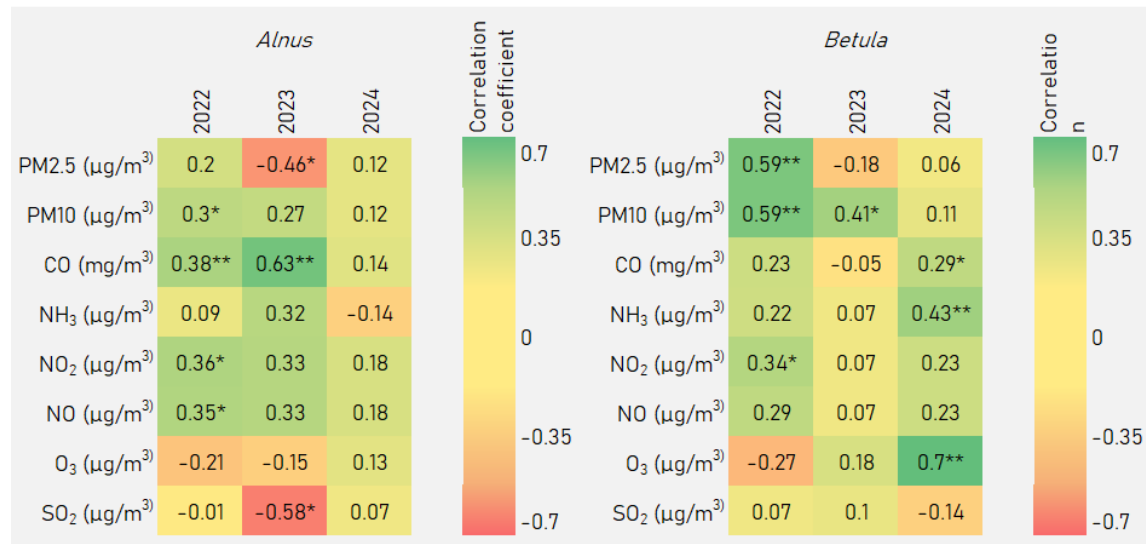
While analysing 2022-2024 data, it was observed that the longest pollen season was for Poaceae (Figure 2A). The Betulaceae pollen season duration was 36-45 days on average. The results show that total pollen concentrations identified during the pollen season tended to increase over the three-year period (Figure 2B). The observed changes may have been driven by meteorological conditions, particularly air temperature and relative humidity (Figure 1). After assessing the impact of meteorological conditions 40 days prior to the start of the pollen season, it was observed that the pollen season start could be related to air temperature, especially for plants (*Alnus*, *Betula*; Figure 2C) flowering in early spring. Simultaneously, the earlier start of the pollen season could be linked with higher relative humidity 40 days prior to the start of the season, particularly for *Alnus* (Figure 2D).

Links between airborne pollen and air quality

The assessment of the links between pollen concentrations and air pollution indicators showed that pollen concentrations more often correlated positively with PM2.5, PM10, NO₂, NO, and CO, while correlations with SO₂ and O₃ were mostly negative (Figure 3).

The correlations established with NH₃ were statistically insignificant in most cases, except for a few positive correlations. The highest correlation coefficients were found between pollen concentrations and O₃, as well as PM2.5 (*Betula*: $r = 0.70$, $p < 0.01$ and $r = 0.59$, $p < 0.01$), CO and SO₂ (*Alnus*: $r = 0.63$, $p < 0.01$ and $r = -0.58$, $p < 0.05$), as well as CO (*Poaceae*: $r = 0.53$, $p < 0.01$). According to the limit values of air pollutants applied in Lithuania (Lithuanian Environmental Protection Agency, 2025), it was found that in 2022-2024, exceedances of the limit values for PM10, NO₂, NO, and NH₃ pollutants were recorded in Vilnius.

The evaluation of the relationships between pollen concentrations and air pollution was conducted using data collected 40 days before the start of the pollen season for each pollen type (Figure 4).



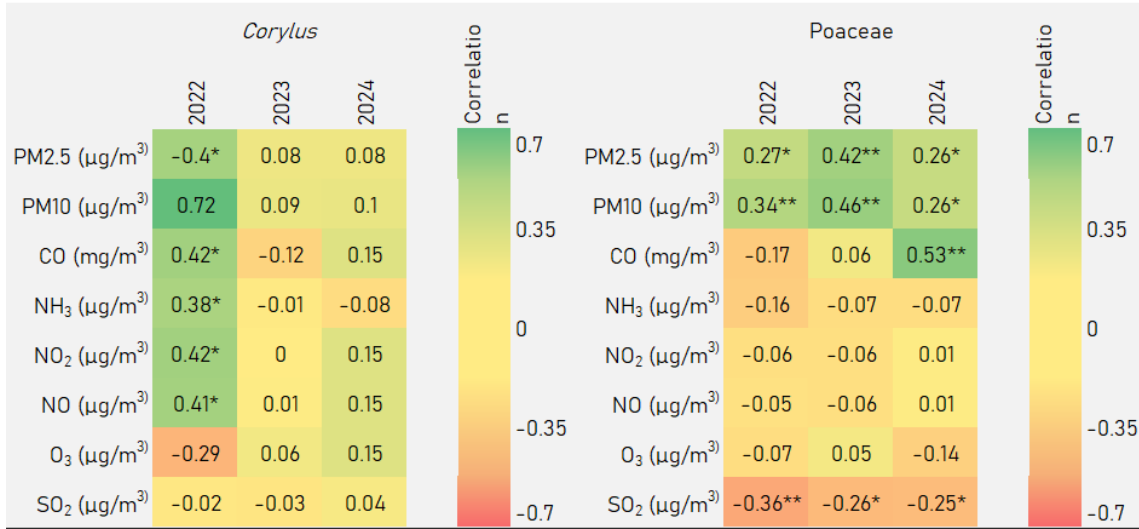


Figure 3. Statistical associations between daily pollen concentrations of *Alnus*, *Betula*, *Corylus*, *Poaceae* and air pollution in 2022-2024 (* $p < 0.05$, ** $p < 0.01$)

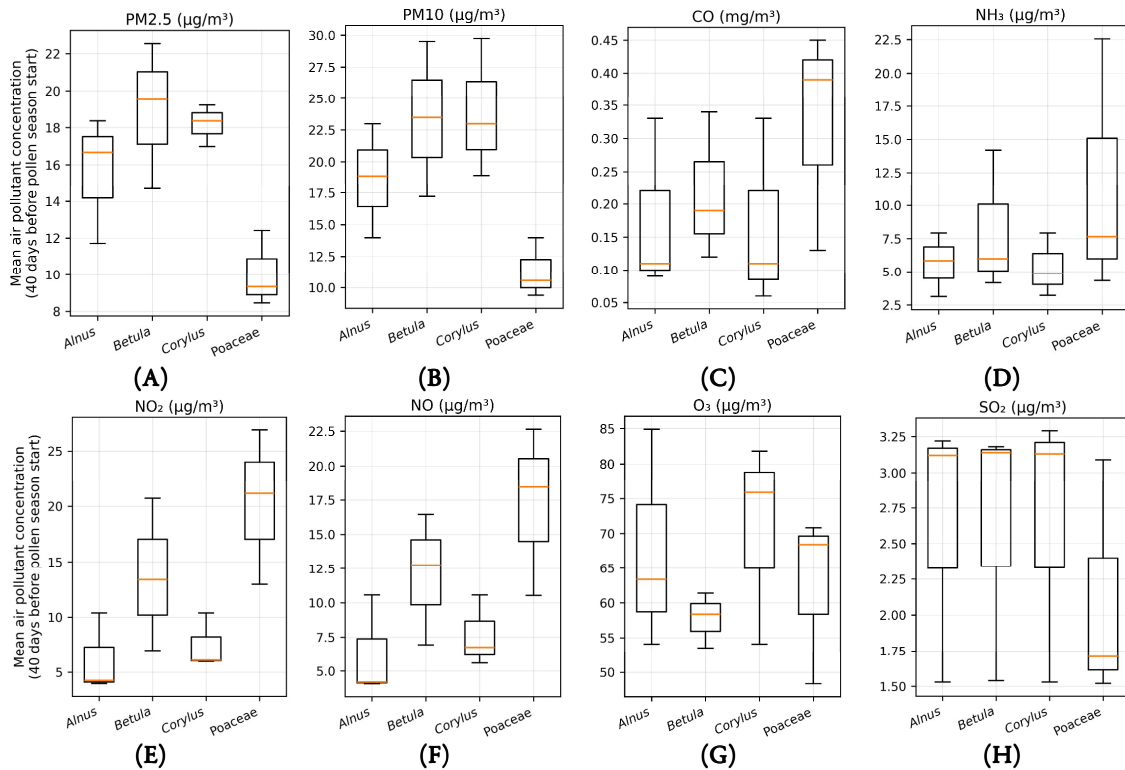


Figure 4. Distribution of air pollutant concentrations 40 days before the start of the pollen season (2022-2024); (A) mean values of PM_{2.5} pre-season concentration, (B) mean values of PM₁₀ pre-season concentration, (C) mean values of CO pre-season concentration, (D) mean values of NH₃ pre-season concentration, (E) mean values of NO₂ pre-season concentration (F) mean values of NO pre-season concentration (G) mean values of O₃ pre-season concentration (H) mean values of SO₂ pre-season concentration

It was observed that 40 days before the appearance of Betulaceae pollen, especially *Betula*, high PM concentrations were detected. *Betula* SPI was the highest among the pollen studied in this research. Comparatively higher NO₂ and NO concentrations were observed in the case of Poaceae relative to other pollen types. In Figure 4, the results show a higher NO_x concentration in the air during the 40-day period following the first appearance of Poaceae pollen.

Discussion

In the present study, correlations between *Alnus*, *Betula*, *Corylus*, Poaceae pollen concentrations and meteorological parameters, as well as air quality indicators in Vilnius in 2022-2024, were analysed using data from automatic pollen measurements. Our results showed that total pollen concentrations calculated during the study period increased annually. However, when evaluating data from automatic pollen measurements, several factors must be taken into account. When evaluating high-resolution data, it is necessary to consider that the algorithms for identifying bioaerosols measured by automatic devices are continually improving (Daunys *et al.*, 2024; Tummon *et al.*, 2024). For this reason, interannual differences and overall changes in concentration trends must be interpreted while accounting for the possible methodological uncertainty associated with classification algorithm accuracy and potential changes over time. Nevertheless, the results obtained show that high-temporal-resolution automated pollen monitoring enables the assessment of pollen concentration fluctuations and their relationships with environmental variables. Pollen identification using automatic pollen measurements is relevant for both expanding knowledge on aerobiological processes and developing forecasting solutions.

Analysis of pollen seasonality showed that the pollen seasons of *Alnus*, *Corylus*, and Poaceae started earlier during the 2022-2024 period (see Figure 2). Studies conducted in Central Europe show similar results, for example, an advanced start of the pollen season by a few days was recorded for *Betula* and Poaceae throughout a 4-year study period in Augsburg, Germany (Muzalyova *et al.*, 2021). Meanwhile, a study in Poland found that the *Betula* pollen season also shifted to an earlier start during a period of 15 years, although to a small extent (Grewling *et al.*, 2012). Studies conducted in northern Africa and southern Europe show mixed results; for example, a delayed season was observed in Morocco due to decreasing temperatures (Boullayali *et al.*, 2021), whereas no trends towards an earlier season were recorded in Spain (Ruiz-Valenzuela and Aguilera, 2018). The changes observed in Vilnius are related to specific mid-latitude meteorological conditions and the phenological response of plants (Romanovskaja and Bakšienė 2020; Ciani *et al.*, 2021). For example, particularly low *Corylus* concentrations recorded in 2023 (only 71 pollen/m³) compared to 2024 (1824 pollen/m³), confirm that even with little to no change in local vegetation, meteorological factors remain one of the key determinants of concentration levels (Piotrowska-Weryszko, 2013; Oduber *et al.*, 2019). Although the changes identified in the study cannot be directly linked to long-term trends, the study confirms the importance of biogeographical context by showing that local meteorological conditions and plant phenology must be considered when comparing results across regions.

Our study confirmed that meteorological parameters and airborne pollen revealed a positive correlation between pollen concentration and air temperature and a negative correlation with relative humidity. These results are consistent with the findings of other studies in Lithuania (Veriankaitė, 2010a; Šaulienė *et al.*, 2019; Pipiraitė-Januškienė *et al.*, 2025) and similar regions (Puc, 2012; Muzalyova *et al.*, 2021), as well as in southern regions with warmer climatic conditions (Ruiz-Valenzuela and Aguilera, 2018; Boullayali *et al.*, 2021). Higher temperatures are associated with anther dehiscence (Ravindra *et al.*, 2022), while higher humidity strongly affects anther opening (Bianchini and Pacini, 1996) and is associated with increased pollen moisture (mass)

(Oduber *et al.*, 2019), which may limit pollen dispersal. A weak but negative correlation with precipitation confirms that precipitation induces deposition of airborne pollen (Schramm *et al.*, 2021; Kumar *et al.*, 2022). The associations between wind speed and Poaceae pollen dispersal (Kluska *et al.*, 2020) highlight the role of wind in pollen transport. Spanish researchers report that the concentration of woody plant pollen in the air was positively correlated with wind speed, especially when it exceeded 36 km/h. (Chico-Fernandez and Ayuga-Tellez, 2025). It can be assumed that the effect of wind speed may be taxonomically specific and that its significance varies for different plant groups and locations. Also, more intense pollen dispersal is expected during a shorter season. In this study, *Alnus* pollen season in 2023 is shorter with a higher daily pollen concentration. Similar findings have been reported in studies by other researchers; for example, Piotrowska-Weryszko (2013) showed that the highest *Alnus* pollen concentrations in Poland were observed during shorter seasons. A 19-year study (Pipiraitė-Januškienė *et al.*, 2025) shows that *Alnus* and *Betula* pollen concentrations and season duration varied depending on the method used to define the pollen season. This indicates that the comparability of seasonality indicators depends on the methodology used to determine pollen season. According to scientific evidence, meteorological conditions also play a significant role in shaping the pollen season. For example, in *Corylus* and Poaceae, meteorological conditions influenced pollen season duration, consistent with general trends across Europe (Schramm *et al.*, 2021). Assessments by Myszkowska (2014b) showed that temperature fluctuations 30 days prior to pollination are significant when forecasting the start of pollen season. This supports the assumption that shift of air temperature in February and March may shift phenological phases (Figure 2), as we observed in Vilnius during 2022-2024. In general, recognised patterns indicate that changes in the pollen season may be influenced by a range of environmental factors.

Our results showed that pollen concentrations may be associated with air pollution. Hidalgo-Barquero *et al.* (2025) note that strong correlations with PM_{2.5} and CO are not always found, although in the case of some taxa, higher pollen concentrations may be associated with higher O₃ concentrations. The interpretation of the effects of O₃ on pollen in the researchers' studies is noteworthy: they claim that high O₃ concentrations can shorten the pollination period of plants, but oxidative stress can also be associated with more intense pollen production (Duque *et al.*, 2021). Our study observed a trend whereby higher concentrations of PM and NO_x were associated with higher levels of airborne pollen. As well as in the case of *Betula*, the highest concentrations were observed at elevated PM_{2.5} levels and with increased O₃ concentrations; meanwhile, for *Alnus* and *Corylus*, higher concentrations were observed with higher CO levels in the air (see Figure 3). Pollen can act as a carrier of PM or break down into smaller fragments, thereby directly increasing the concentration of fine particles in the air, while elevated O₃ levels can shorten the pollination period (Oduber *et al.* 2019). Despite the correlation between pollution and pollen levels, it is also important to note that the observed relationships between pollen concentrations and air pollutants may reflect shared meteorological factors rather than direct causal effects. Furthermore, more controlled experiments are needed to better understand the direct mechanisms by which pollutants may influence pollen behaviour in the atmosphere.

In summary, our study expands current knowledge of the links between pollen dispersion and meteorological parameters, as well as air quality indicators, in urban environments using automated high-resolution monitoring data. At the same time, several limitations of interpretation have become apparent: the short (three-year) data series limits the assessment of long-term patterns, and the continuous improvement of classification algorithms (Daunys *et al.*, 2024; Tummon *et al.*, 2024) dictate the need to cautiously evaluate interannual differences in pollen concentrations. It should be noted that next-generation automated devices can help provide a better understanding of bioaerosol distribution in the air (Smith *et al.*, 2022), although long-term observations with these devices remain limited. The results of our study suggest that the pre-seasonal background of air pollution can be an informative additional explanatory component, but its role should be verified in longer time series. These findings advance knowledge in aerobiology by showing that automated monitoring data can be used to analyse pollen concentration and environmental factors, and to propose

possible explanations for the selection of predictive environmental variables, while clearly defining methodological limitations.

Conclusions

The results indicate that pollen dispersion patterns in Vilnius are related to meteorological parameters and air pollution, with higher air temperature and decreasing relative humidity directly promoting pollen release and the emission of bioaerosols into the atmosphere. The analysis showed that both pre-seasonal preparation for the season (40 days before pollination) and instantaneous weather conditions (hourly temperature, humidity, and wind) determine the variations in pollen concentration for *Alnus*, *Betula*, *Corylus*, and Poaceae. A positive correlation with PM_{2.5} and, in the case of *Betula*, with O₃ indicates a potential interaction with air pollutants in an urban environment. High-resolution automatic monitoring data can contribute to a better understanding of pollen distribution in relation to environmental and air quality factors. To assess the identified interannual changes in pollen concentrations more reliably and minimise the impact of automated recognition algorithm variability, it is advisable to continue high-resolution observations over longer time series, while integrating laboratory tests to further explore the potential interactions with air pollutants. It is also reasonable to develop forecasting models that include pre-season meteorological and air quality indicators as significant variables for pollen dispersion in urban areas.

Authors' Contributions

Conceptualisation: LŠ and IŠ; Data curation: AŽ and LŠ; Formal analysis: AŽ, LŠ and IŠ; Funding acquisition: LŠ and IŠ; Investigation: AŽ, LŠ and IŠ; Methodology: AŽ and LŠ; Visualisation: AŽ and LŠ; Writing - original draft: AŽ and LŠ; Writing - review and editing: AŽ, LŠ and IŠ.

All authors read and approved the final manuscript.

Acknowledgements

This study was partially funded under Research Contract No. 2.13 Mr-15600 SU-369.

Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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