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Influence of meteorological variables and air pollutants on measurements from automatic pollen sampling devices

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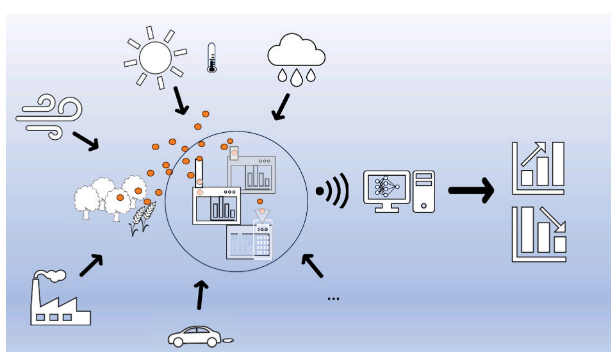
HIGHLIGHTS

- First evaluation of weather and air pollution influence on automatic pollen monitors
- Systems' (device + algorithm) results were mainly impacted by weather variables
- Peaks of particulate matter causing misclassifications might add a bias in counts
- Other air pollutants do not seem to be major factors influencing the measurements
- Including environmental conditions in algorithms can reduce false positives

GRAPHICAL ABSTRACT



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A B S T R A C T

This study examines the influence of meteorological factors and air pollutants on the performance of automatic pollen monitoring devices, as part of the EUMETNET Autopollen COST ADOPT-intercomparison campaign held in Munich, Germany, during the 2021 pollen season. The campaign offered a unique opportunity to compare all automatic monitors available at the time, a Plair Rapid-E, a Hund-Wetzlar BAA500, an OPC Alphasense, a KH-3000 Yamatronics, three Swisens Polenos, a PollenSense APS, a FLIR IBAC2, a DMT WIBS-5, an Aerotape Sextant, to the average of four manual Hirst traps, under the same environmental conditions. The investigation aimed to elucidate how meteorological factors and air pollution impact particle capture and identification efficiency.

The analysis showed coherent results for most devices regarding the correlation between environmental conditions and pollen concentrations. This reflects on one hand, a significant correlation between weather and airborne pollen concentration, and on the other hand the capability of devices to provide meaningful data under the conditions under which measurements were taken. However, correlation strength varied among devices, reflecting differences in design, algorithms, or sensors used. Additionally, it was observed that different algorithms applied to the same dataset resulted in different concentration outputs, highlighting the role of algorithm design in these systems (monitor + algorithm).

Notably, no significant influence from air pollutants on the pollen concentrations was observed, suggesting that any potential difference in effect on the systems might require higher air pollution concentrations or more complex interactions. However, results from some monitors were affected to a minor degree by specific weather variables.

Our findings suggest that the application of real-time devices in urban environments should focus on the associated algorithm that classifies pollen taxa. The impact of air pollution, although not to be excluded, is of secondary concern as long as the pollution levels are similar to a large European city like Munich.

1. Introduction

The concentration of airborne pollen is measured worldwide (Buters et al., 2018) for a large variety of applications. The main focus is the effect on the allergic population, which is approximately 10–30 % in most countries (Pawankar et al., 2013), with substantial economic impact (Stróżek et al., 2019). Allergenic pollen is the primary trigger of seasonal allergies and causes the highest number of sensitization (e.g., Heinzerling et al., 2009). Airborne pollen concentrations can aid allergologists and other medical practitioners in providing more accurate diagnosis and tailored treatment strategies, thereby enhancing the quality of life for millions of people.

Measurements of pollen concentrations also have several other applications, e.g. in evaluation of climate change, where pollen records can serve as bioindicators, reflecting past climatic conditions and aiding in forecasting future climate trends (Damialis et al., 2019; Ziska et al., 2019). Knowledge regarding airborne pollen concentrations is also applied in agriculture, where precise pollen monitoring can improve crop breeding, pollination strategies, and overall productivity (Orlandi et al., 2020; Oteros et al., 2014). Therefore, improving the accuracy of pollen sampling devices can profoundly enhance these application areas.

Airborne pollen monitoring is a common practice worldwide (Buters et al., 2018), and has historically been performed with different manual samplers e.g., Hirst, Cour, or Rotorod. The Hirst-type samplers are used globally (Buters et al., 2018), and considered as the reference instrument for the European Aerobiology Society (EAS) (Galán et al., 2014). Furthermore, they are included as the reference instrument in the European Standard (EN16868 2019). Hirst traps require a laborious manual procedure and expertise to identify pollen taxa, which entails a delay of 1–10 days in the provision of pollen concentration data, among other limitations (Oteros et al., 2017; Suarez-Suarez et al., 2023; Adamov et al., 2021).

Recent technological advancements have facilitated the development of automatic samplers. These automatic instruments potentially overcome many limitations of Hirst-type traps. However, they are based on a variety of different technologies (induced fluorescence, digital holography, and image recognition) and currently no standard exists for automatic measurements (although one is under development; Buters et al., 2022; Clot et al., 2020; Tummon et al., 2022).

Due to their ability to deliver data in real-time at high temporal resolution, some of these devices have been already adopted in monitoring networks to support allergy sufferers, researchers, and various organisations monitoring pollen levels in the environment (Oteros et al., 2020; Tešendić et al., 2020; Erb et al., 2023).

Important questions in relation to these new instruments are still open, i.e., how meteorological factors influence their sampling efficacy. Furthermore, in order to preserve historical time series, the magnitude of this impact in comparison to the one exerted on Hirst type traps should be revealed.

Meteorological factors are confounding variables that influence measured pollen concentrations in different ways, e.g. by impacting the sampling efficiency of different instruments. For example, the inlet on the Hirst trap is oriented into the wind, while most automatic instruments sample air from all angles (360° around a stationary sampling inlet). Wind speed and air pressure may also play a key role on impaction properties or the scanning of particles. Strong winds or heavy rain may interfere with instrument operation (for example by saturating the trigger capacity), which may lead to inaccurate measurements. Also, variations in temperature or high humidity episodes may change the physical characteristics of pollen (e.g. Mills et al., 2023a; Bozic and Siber, 2022; Griffiths et al., 2012; Pope, 2010). It is important to study all these confounding variables on automatic instruments to reduce both misclassifications and biases.

The accuracy and reliability of pollen measurements can also be significantly influenced by other environmental factors such as air pollution (Miki et al., 2017). Air pollutants are therefore also confounding variables that can impact pollen measurements since pollutants such as particulate matter, nitrogen oxides, sulphur dioxide, and ozone can interact with pollen grains in complex ways (Sénéchal et al., 2015). For example, certain pollutants can cause the outer layers of pollen grains to rupture, releasing smaller allergenic sub-pollen size particles that currently cannot be measured with methods other than DNA- or allergen-quantification. Chemical pollutants may also react with the proteins on the pollen grain surface (Lu et al., 2014), change the grain's shape (Azzazy, 2016), deposit on the surface of the pollen (Ortega-Rosas et al., 2021) and likely also affect their emission spectra (Roshchina and Karnaukhov, 1999), thus altering the identification accuracy rates. Given these influences, understanding and accounting for the effects of weather and air pollution on different instruments used for pollen monitoring is essential.

To investigate and potentially mitigate the impact of environmental variables, we utilise the insights gleaned from the EUMETNET AutoPollen-COST ADOPT intercomparison campaign conducted in Munich, Germany, from March to July 2021 (Maya-Manzano et al., 2023). This campaign enabled a comparison of measurements of airborne pollen concentrations from all automatic pollen monitors commercially available at the time, as well as some prototypes. Having all instruments at the same location in the same environmental conditions, allows us to address certain questions, for example, whether some automatic instruments have issues with the recognition of specific pollen taxa or whether meteorology or air pollutants (AQ) influence the measurements in any way.

In this study we aim to explore the relationship between meteorology, AQ and pollen concentrations at high temporal resolution (3-hourly) for each of the automatic instruments. Our hypothesis is that environmental conditions may influence the pollen measurements of the various monitors in different ways because of the different sampling principles and different data processing algorithms. Any such impacts could influence the choice of which system is best adapted for specific environmental conditions and for a particular purpose.

2. Materials and methods

2.1. Campaign site and instruments

The campaign was performed in the outskirts of Munich, Germany, as part of the EUMETNET AutoPollen-COST ADOPT intercomparison campaign 2021 (Maya-Manzano et al., 2023). Instruments were placed on the roof of a building at the Helmholtz Center (Fig. 1) from 3 March to 15 July 2023. Fig. 1A shows the location of the experiment, which was near a protected area for military instruction with natural grassland and small patches of deciduous forest with birch trees to the north of the site. Several other pollen sources also surround the building. A more detailed description of the surrounding vegetation can be found in Triviño et al. (2023).

Fig. 1B shows the placement of the different devices during the experiment. A total of four Hirst-type volumetric traps were located on the roof, as well as the following automatic instruments: Flir IBAC-2, DMT WIBS-5, Hund Wetzlar BAA500, Plair Rapid-E, PollenSense Automated Airborne-Particle Sensor (APS), Yamatronics KH-3000, Swisens Poleno Mars, Swisens Poleno Neptune, Swisens Poleno Jupiter and three Alphasense OPC N3 (see Maya-Manzano et al., 2023, Martínez-Bracero et al., 2022, Mills et al., 2023b and Buters et al., 2022 for detailed technical description of these instruments). For some devices, several algorithms for the classification of pollen taxa were applied to the same dataset. From here on, we use the term "system" to refer to the combination of "instrument + algorithm". For example, different algorithms were applied to the dataset collected by the Poleno Jupiter, therefore we refer to different systems for the same Poleno Jupiter instrument.

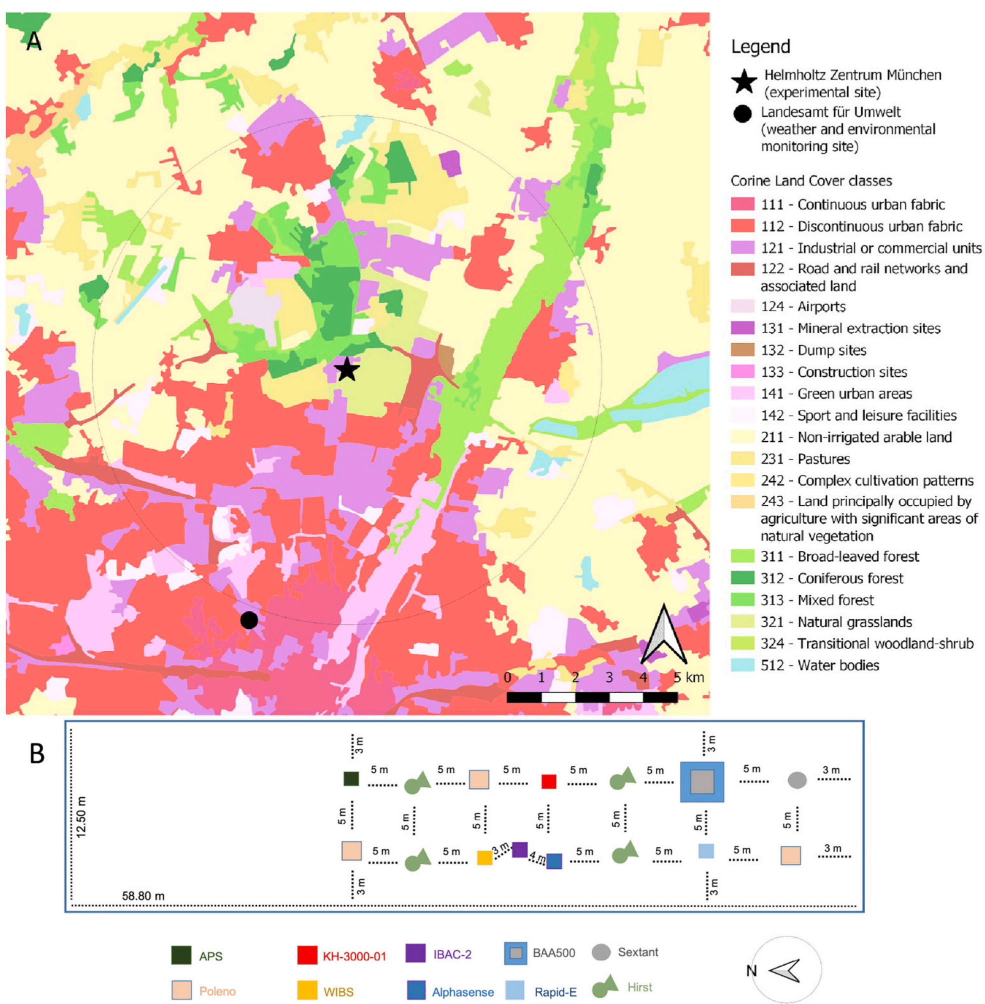

Fig. 1. A. Location of the experimental pollen measurement site (48.220912° N, 11.595590° E), and meteorological and environmental monitoring stations. Main land uses in the surroundings of the experiment site are depicted. B. Location of the pollen monitors on the roof (10.5 m above ground) of the experimental site at the Helmholtz Zentrum München.

2.2. Pollen data

The total pollen concentration from each individual automatic instrument and system was analysed and for a number of single pollen taxa, when available. This study includes the main pollen taxa for which sufficient data were available, as suggested by Maya-Manzano et al. (2023): *Betula* (average size of 22 μm), *Poaceae* (average size of 35 μm), *Fraxinus* (average size of 22 μm) and *Quercus* (average size of 38 μm). In addition, to match the device with the lowest time resolution during the campaign, the BAA500, all other pollen concentrations from instruments with higher temporal resolution measurements were averaged to 3-hourly means. For each instrument, total pollen concentrations were calculated as the sum of all concentrations of the different classes included in their software, following Maya-Manzano et al. (2023), except for IBAC2 and Alphasense, which can only provide estimates of total pollen concentrations without taxon specification. These two instruments, together with APS, present some gaps in their data due to technical or logistical settings during the campaign (Maya-Manzano et al., 2023).

As a baseline dataset, we calculated the average daily and 3-hourly pollen concentrations from the four Hirst-type traps (Fig. 2), following the same procedure as described in Maya-Manzano et al. (2023). The average flow values for the traps were 14.43 ± 0.32 L/min for trap A, 13.38 ± 0.26 L/min for trap B, 13.21 ± 0.25 L/min for trap C and 13.39 ± 0.25 L/min for trap D. The coefficient of variation between the observations of the four traps differed depending on the pollen type. According to the results provided by Triviño et al. (2023), the mean and standard deviation of the coefficient of variation for the eight most abundant pollen taxa captured by the Hirst traps was 40.5 ± 2.5 % and 19.0 ± 5.1 % for hourly and daily values respectively. The mean of all four Hirst-type traps is hereafter simply referred to as "Hirst measurements".

The time series of pollen concentrations from the selected taxa during the campaign is presented in Fig. 2. According to Rojo et al. (2020), *Betula* was the most abundant pollen taxa in the city of Munich during the period 2006–2016, as also seen in the data from the campaign (Table 1). In Munich, *Fraxinus* pollen is typically more abundant than *Poaceae* and *Quercus* (Rojo et al., 2020). However, in 2021 the *Fraxinus* seasonal pollen integral was considerably lower than in previous years, as reported by Rojo et al. (2020).

Table 1
Summary parameters of the analysed pollen taxa from the 2021 campaign.

Pollen	Start date	Peak date	End date	Season duration (days)	Seasonal pollen integral (grains/m^3)	Peak value (grains/m^3)
Fraxinus	2021-03-30	2021-04-01	2021-04-29	31	1095	161
Betula	2021-04-09	2021-04-22	2021-05-10	32	3082	604
Quercus	2021-05-06	2021-05-10	2021-05-31	26	729	140
Poaceae	2021-05-26	2021-06-12	2021-07-07	43	2979	240

2.3. Meteorological variables and air pollutants

Meteorological data were obtained from the *Deutsche Wetterdienst* (DWD) (https://opendata.dwd.de/climate_environment/CDC/observations_germany/) from the nearest weather station, 7 km from the experimental site (Helene Weber Allee, Munich, 48.1635°N, 11.5437°E). Hourly data of air temperature (°C), rainfall (mm), wind speed (m/s), wind direction (°), air pressure (hPa), sunshine (hourly sum, in minutes) and relative humidity (%) measurements were obtained at a height of 2 m. A summary of the meteorological variables during the study are shown in Table 2.

Hourly data for selected Air pollutants (AQ) were obtained from the *Landesamt für Umwelt* (LfU) (www.lfu.bayern.de). The concentrations of $PM_{2.5}$, PM_{10}, O_3, NO_2 and NO (Table 2) were obtained from a background roof-level station at Lothstrasse, Munich (48.1555°N 11.5534°E), located 8 km from the experimental site.

All meteorological and air pollutant data were averaged from hourly

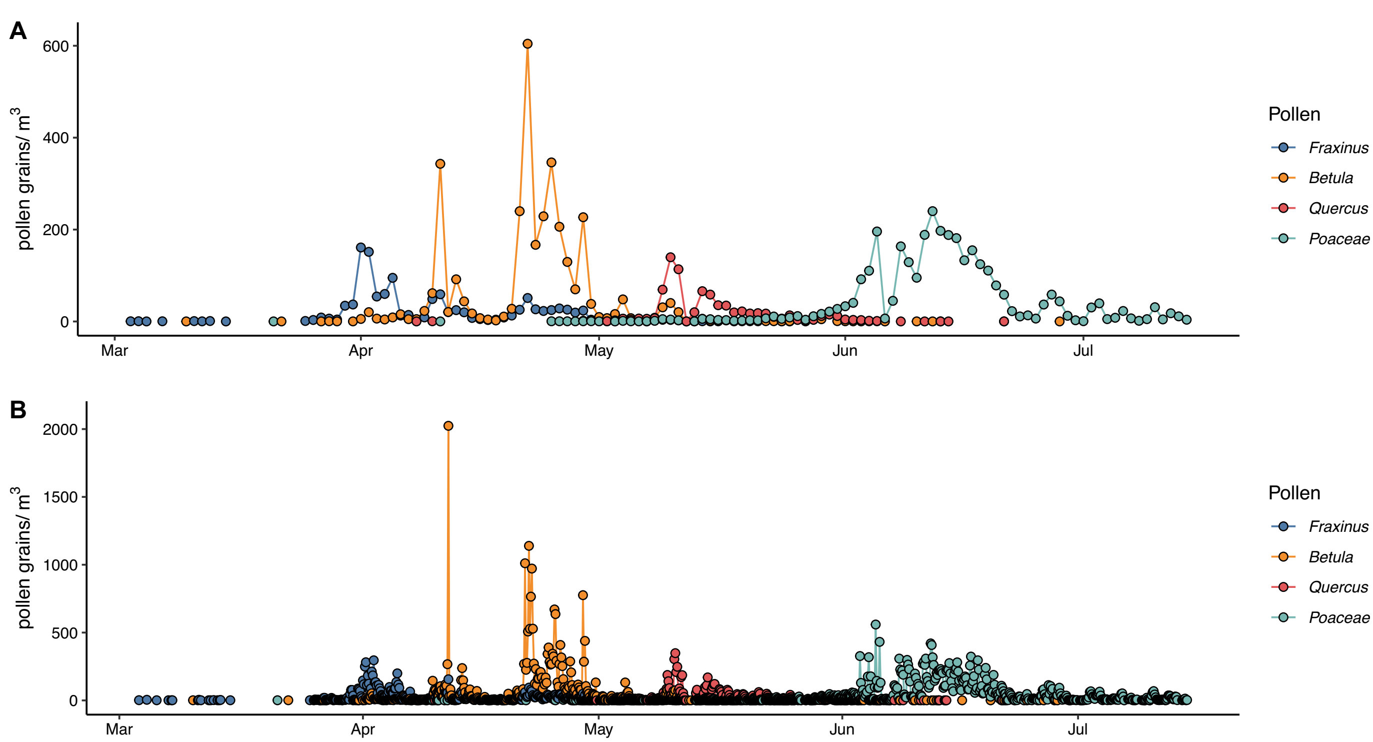

Fig. 2. Pollen concentration as measured by the average of the four Hirst-type traps during the intercomparison campaign 2021. A. Daily pollen concentrations. B. 3-hourly pollen concentrations.

Table 2
Average values (for the entire campaign) of the meteorological variables and air pollutants (hourly concentrations).

	Hourly rainfall (mm)	Average air temperature (°C)	Relative humidity (%)	Wind speed (m/s)	Wind direction (°)	Sun (minutes per hour)	Air pressure (hPa)	CO (mg/m^3)	NO (µg/m^3)	NO2 (µg/m^3)	O_3 (µg/m^3)	$PM_{2.5}$ (µg/m^3)	PM_{10} (µg/m^3)
Min	0	−4.1	16	0	10	0	941.7	0.1	0	3	1	0	0
1st Qu	0	6	50	1.8	160	0	952.2	0.2	1	11	36	3	7
Mean	0.2	11.7	65.5	2.9	216.6	23	955.8	0.4	5	21	56	8	14
3rd Qu	0	16.7	83	3.6	280	55	959.4	0.5	5	26	74	10	18
Max	37.5	31.6	96	11.1	360	60	971.4	1.7	189	110	169	48	168

to a 3-hourly resolution.

2.4. Statistical analysis

First, the influence of environmental conditions on the automatic monitors was estimated using a Spearman correlation analysis between each weather and AQ variables and observations from each measurement system at both daily and 3-hourly resolution. Then, we calculated the "distance to the Hirst", to evaluate the agreement between each system and the mean of the four Hirst traps, used as baseline. The distance was the difference of the absolute Spearman correlations of all weather and AQ variables.

Second, we considered the differential impact of the weather and AQ variables on observations from each system. For this, we calculated the correlation between each variable and the ratio between the automatic and manual Hirst concentrations. The ratio ranges from 0 to infinity, with a ratio = 1 meaning that both devices measure the same pollen concentration during the target 3 h while, for example, a ratio of 2 means the automatic device measures double the pollen concentration. We used the average of four Hirst as the baseline since the manual instrument is still the most frequently used method for pollen monitoring, part of the standard method of the European Aerobiology Society (EAS), and most of the time series are based on this method.

We carried out a further analysis to evaluate the relationship between the meteorological variables and the pollen concentrations derived from the automatic systems. For this analysis, we focused on temperature and humidity, which were the variables that were shown to have the strongest relationship with the pollen measurements from the results of the first correlation analysis. We calculated four interquartiles for three weather variables related with both temperature and humidity; temperature, humidity and rainfall, to explore whether the sampling efficiency varied within these ranges.

3. Results

The analysis of the influence of the weather and AQ variables was performed on both 3-hourly and daily concentrations of pollen measured with the Hirst traps and automatic systems to evaluate whether we could find differences between diurnal and seasonal patterns. Fig. 3 shows the results of the Spearman correlations. The points on the graph represent the correlation coefficient between each variable (y axis) and each system (with different colours).

Overall, most systems show similar correlations with the environmental factors, suggesting that the systems measure similar pollen

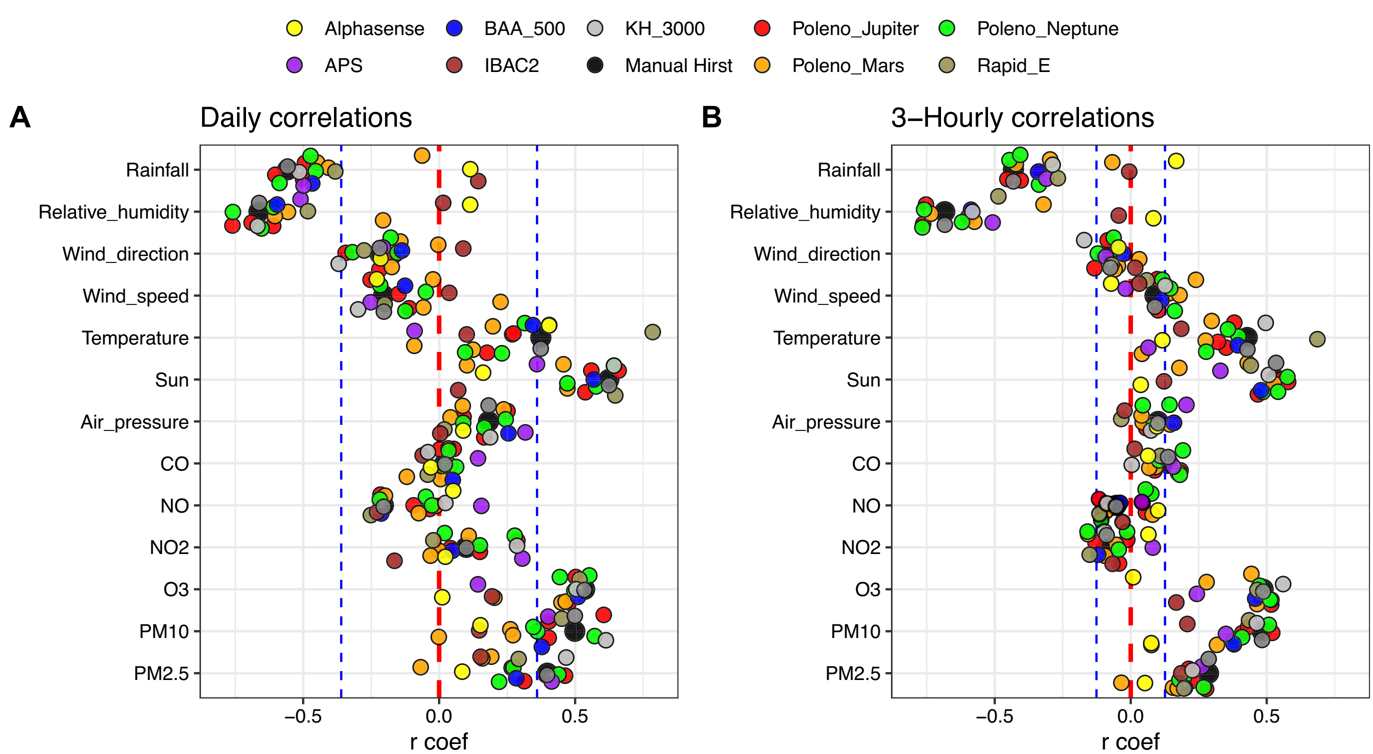

Fig. 3. Correlation between environmental conditions (meteorology and air pollution) and daily (A) and 3-hourly (B) airborne total pollen concentrations as measured using manual Hirst-type traps and with automatic devices. Vertical blue lines show the limit of significant correlations, i.e. correlations between the two blue lines are non-significant.

concentrations under different meteorological situations and/or that all devices provide sensible information about total airborne pollen levels. However, not all devices show exactly the same response in either direction or magnitude. In addition, some devices (Alphasense, APS, IBAC2) have very frequent non-significant correlations with certain conditions, showing a pattern different to the other automatic monitors. Since these devices/algorithms also showed low correlations with the Hirst data themselves, such disagreement is not surprising.

We can observe in Fig. 3 several points of the same colour representing the different systems (i.e., monitor + algorithm) of a specific device. In certain cases there is a remarkably wide spread in system values for a single device, e.g., for Poleno Mars. It is interesting to note that the correlations from the Hirst traps usually present an average value compared to the automatic devices.

The correlations observed with both daily and 3-hourly resolutions are very similar, discarding that the distribution within a daily pattern of the environmental conditions analysed was impacting differently on the mean daily distributed patterns for the same conditions.

We used "distance to the Hirst" as an indicator of the agreement between an automatic device and the Hirst baseline. Table 3 shows the mean distance of the correlations of each system to the average of the four Hirsts.

Overall, the BAA500, Poleno Jupiter, Poleno Neptune, and KH-3000 show similar average distances, followed by the other systems. As expected, the BAA500, a measurement system based on the same principle as the Hirst method (i.e., impaction and image identification), exhibits similar correlations with environmental conditions. However, among all systems, one of the Poleno Jupiter demonstrates the shortest average distance to the correlations seen with the Hirst method.

Fig. 4 shows results from the correlation analysis between weather and AQ variables and the 3-hourly ratio (automatic:manual) between the total pollen concentrations measured by each of the automatic devices and the mean of the four Hirst-type traps. Each point in the graph represents a correlation between 3-hourly environmental conditions and the 3-hourly automatic:manual ratio.

The points with zero correlation indicate that the influence of environmental conditions on the ratio between Hirst and the given automatic device is null. In other words, these environmental conditions do not seem to have a significant effect on the difference in pollen concentration measured by Hirst compared to the automatic devices. In contrast, the points with a high correlation indicate that the given environmental condition affects the Hirst and the automatic device differently, resulting in differences in the pollen concentrations measured by each device.

Our results suggest that certain environmental conditions have a more significant effect on the ratio of the manual to automatic pollen

Table 3
Difference of absolute Spearman correlations of daily pollen concentrations and environmental conditions between the average of the manual Hirst-type traps and different automatic monitoring systems. Systems are presented in decreasing order according to the average distance.

System	Average distance	Air pressure	Sun	Temperature	Wind speed	Wind direction	Relative humidity	Rainfall	$PM_{2.5}$	PM_{10}	O_3	NO_2	NO	CO
Hirst	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Poleno Jupyter 1	0.06	0.07	0.06	0.11	0.06	0.05	0.05	0.06	0.09	0.09	0.02	0.06	0.01	0.02
BAA500	0.06	0.07	0.05	0.03	0.08	0.08	0.07	0.09	0.11	0.12	0.02	0.05	0.01	0.03
Poleno Neptune 1	0.06	0.06	0.05	0.06	0.08	0.07	0.05	0.08	0.12	0.14	0.02	0.08	0.01	0.01
Poleno Neptune 3	0.07	0.02	0.02	0.14	0.01	0.10	0.10	0.03	0.04	0.07	0.04	0.18	0.18	0.01
Poleno Jupyter 2	0.08	0.09	0.09	0.20	0.09	0.00	0.03	0.06	0.13	0.10	0.06	0.05	0.11	0.03
KH 3000	0.08	0.01	0.02	0.03	0.09	0.15	0.01	0.04	0.07	0.11	0.03	0.19	0.23	0.06
Poleno Jupyter 3	0.08	0.02	0.04	0.10	0.05	0.13	0.10	0.04	0.07	0.11	0.03	0.19	0.17	0.01
Rapid E	0.11	0.16	0.02	0.41	0.00	0.06	0.18	0.17	0.11	0.05	0.02	0.12	0.05	0.06
Poleno Mars 1	0.11	0.06	0.15	0.18	0.15	0.07	0.11	0.11	0.21	0.24	0.09	0.10	0.01	0.02
Poleno Neptune 2	0.12	0.09	0.15	0.28	0.16	0.04	0.01	0.10	0.18	0.15	0.09	0.05	0.16	0.04
Poleno Mars 2	0.13	0.10	0.17	0.25	0.18	0.04	0.06	0.15	0.24	0.23	0.07	0.01	0.13	0.02
APS	0.18	0.13	0.26	0.46	0.05	0.01	0.15	0.06	0.02	0.10	0.39	0.21	0.36	0.12
Alphasense	0.28	0.09	0.46	0.03	0.03	0.00	0.78	0.67	0.31	0.35	0.52	0.08	0.26	0.05
IBAC2	0.33	0.18	0.55	0.27	0.24	0.31	0.68	0.70	0.25	0.35	0.34	0.26	0.02	0.08
Poleno Mars 3	0.34	0.14	0.52	0.46	0.43	0.21	0.46	0.49	0.47	0.50	0.33	0.13	0.19	0.14

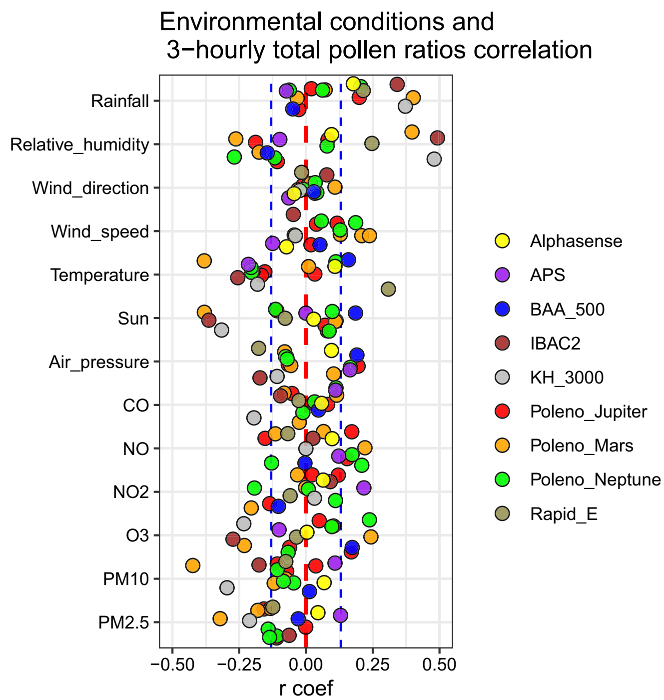

Fig. 4. Correlation between environmental conditions and the 3-hourly ratio between automatic and manually-measured pollen concentrations.

measurements than other conditions. It is, however, important to keep in mind that the Hirst-type traps could also be affected by the environmental conditions and not only the automatic traps, thus results should be interpreted cautiously.

For most of the devices, the environmental conditions do not show significant influences on the total pollen concentration ratios, but some systems seem to be more affected. For example, we can see how rainfall clearly impacts the IBAC2, KH-3000 and some algorithms for the Poleno Mars. The latter two also seem to be correlated with PM, possibly because of misclassifications. The Poleno Mars ratio also correlates with temperature, humidity and solar radiation, variables which are all highly correlated themselves. The Rapid-E shows a somewhat lower bias for the same three parameters. Small deviations are seen with wind speed and wind direction, meaning that all instruments -including the Hirst trap, which is the only instrument with a wind-oriented inlet-, are similarly efficient at sampling particles irrespective of wind speed and direction. Solar radiation, air pressure and all of the gaseous pollutants do not show correlations with the 3-hourly ratios, or very little, which means that there are unlikely to be any impacts of these parameters on the pollen measurements of any device.

Fig. 5 shows similar results, but with values split per pollen taxa. Correlations were different depending on the pollen taxa. One reason could be the differences in environmental conditions during the different pollen seasons.

When all the ratios are near to the red line, the environmental condition does not appear to affect any of the instruments. When all devices show a deviation of the ratio in the same direction that particular environmental condition either affects the Hirst traps, or all the automatic devices in the same way. It is important to note that these correlations are more sensitive to conditions related to false positive classifications because the seasons for individual pollen taxa are shorter. In other words, if a specific pollen is reported out of the pollen season during a period characterised by different conditions, it may lead to the high correlations observed. For example, if we explore the extreme high correlations observed between the ratios for most of the devices and temperature, we see that most instruments show positive correlations in the case of *Betula* and *Fraxinus* (i.e., the automatic devices overestimated these pollen taxa during periods with higher temperature).

The opposite is observed with *Poaceae*. Both *Fraxinus* and *Betula* flower earlier in the season during colder periods. Therefore, misclassifications of these pollen taxa during late spring and summer would lead to positive correlations. In the case of *Poaceae*, flowering occurs during late spring and summer, and thus classification errors during winter would produce the opposite effect. Interestingly, the automatic: manual ratio for *Quercus* is positively correlated with both PM_{10} and $PM_{2.5}$ for all instruments, possibly indicating that these measurements are influenced to some extent by particulate pollution.

We can also identify situations when a single device shows distinctly different behaviour, for example, in the case of air pressure and the Rapid-E.

Fig. 6 presents the environmental conditions during the pollen season of the targeted species. For the late-flowering *Poaceae*, the season has much higher temperatures than for *Fraxinus* and *Betula* which flower earlier (see Fig. 2). Also, the daily average rainfall during the *Poaceae* season is higher. It is also remarkable that the concentration of PM_{10} is considerably lower during the *Quercus* season than the season of the three other taxa.

We explored in more detail the impact of different ranges of temperature and relative humidity on the automatic:manual ratios. Fig. 7 presents the 3-hour ratios of total pollen across different temperature (A) and relative humidity (B) ranges. Only ratios between 0 and 10 are displayed to better visualise the distributions.

In terms of temperature (Fig. 7A), the data show that there is somewhat less variability in the ratio between automatic and manual measurements at higher temperatures (>25 °C). Furthermore, there is a consistent trend showing higher ratios during periods with low temperatures across all pollen. This suggests a pattern where the total pollen ratio is sensitive to temperature fluctuations or a sensitivity of the ratio to low pollen concentrations (usually during low temperature periods). The latter may be the more plausible explication since at low pollen concentrations Hirst-type traps suffer from considerable uncertainty (Adamov et al., 2021).

The relative humidity graph (Fig. 7B) demonstrates a modest increase in ratios with higher humidity levels. This increase is especially pronounced for the Rapid-E, although the KH-3000 also shows a relatively large increase in ratio at higher humidity. For both temperature and humidity the Alphasense has larger variation in the ratio compared to the other instruments, suggesting less stability in its measurements.

4. Discussion

This study aimed to determine for the first time the influence of environmental conditions on the performance of various pollen automatic monitoring devices in a standardized setting.

The recentness of the development of automatic monitors and the relatively short period of operational use to date (e.g., five years for the BAA500, and three for the Poleno and Rapid-E) means that no joint evaluation of the impact of meteorological variables and air quality parameters on these measurements has yet been carried out.

The location of the experiment was ideal for the intercomparison, with few nearby pollen sources affecting the measurements (Triviño et al., 2023). The most important nearby tree pollen source is the deciduous forest to the North, but since SW winds dominated the main part of the measurement campaign (Triviño et al., 2023), this source will have limited impact on the observations. This means that our results are likely representative of instruments' performance in Central Europe.

We first analysed the correlation between various environmental conditions and daily or 3-hourly pollen observations. We found that most systems (monitor + algorithm) were clustered suggesting that all devices provide sensible information about total airborne pollen levels.

Our analysis revealed that most of the automatic devices showed similar correlations with specific weather and AQ variables. This suggests that most weather and AQ variables are confounders on measured

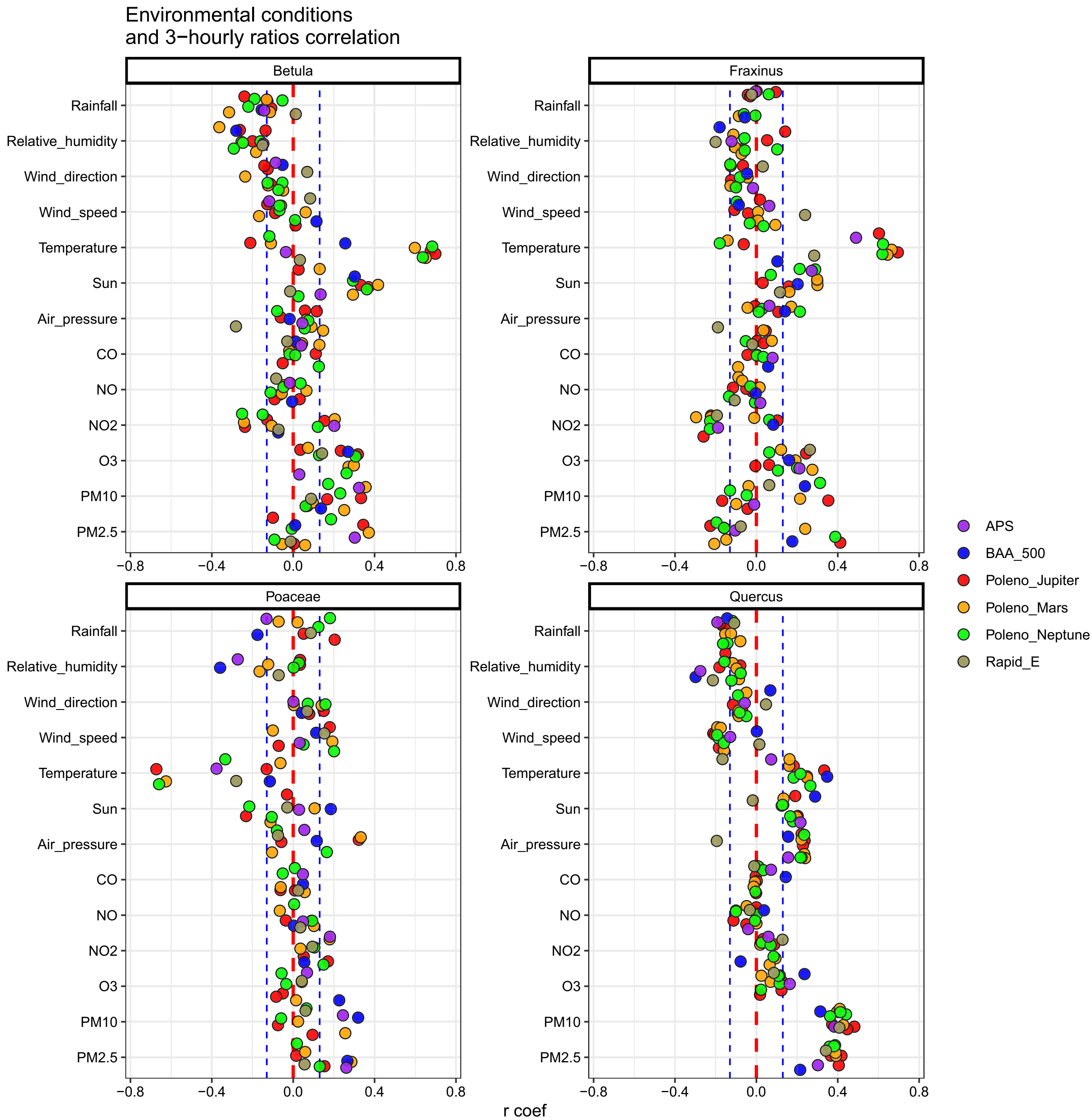

Fig. 5. Correlation between environmental conditions and the 3-hourly ratio of pollen concentrations (automatic:manual) of the four main pollen taxa. Devices for which several algorithms were applied are shown with the same symbol.

pollen concentrations (Fig. 3) as observed in other studies (Ščevková et al., 2020; Adams-Groom et al., 2022).

However, the strength of these correlations varied between the devices, perhaps because each type of monitor may be uniquely impacted by environmental conditions. The cause can be attributed to the specific design, algorithm, or the type of sensor used in each device and how this then affects the measured pollen concentration. Some devices frequently showed non-significant correlations with environmental conditions, suggesting diverse patterns of sensitivity or even a lack of measurements at all, e.g., Alphasense, APS, IBAC2 present data gaps during the campaign.

There is a wide spread of correlation values within different classification algorithms applied to the same device. This may be in part the result of the different proportion of misclassifications between the different algorithms (Maya-Manzano et al., 2023), which leads to different correlations. For instance, in the air of Munich we can find pollen taxa not included in the algorithms, which might have caused the misclassifications and impacted in total pollen.

This combination of technique and algorithm gave diverse concentration outputs, as highlighted by Maya-Manzano et al. (2023). An example of this are the cases of relative humidity and rainfall. Our study also pointed out potential biases that might affect the performance of certain devices under specific environmental conditions. For instance, in Figs. 4 and 5 we observed rainfall and high relative humidity seemed to

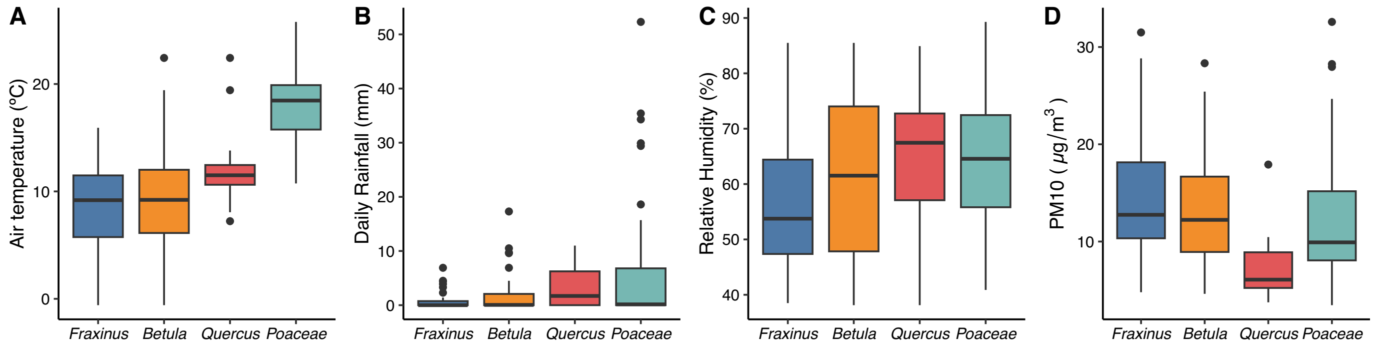

Fig. 6. Variation in environmental conditions during the pollen season of each of the four taxa analysed in this study. A) Average daily air temperature, B) cumulated daily rainfall, C) average daily relative humidity, and D) average daily PM_{10} concentration.

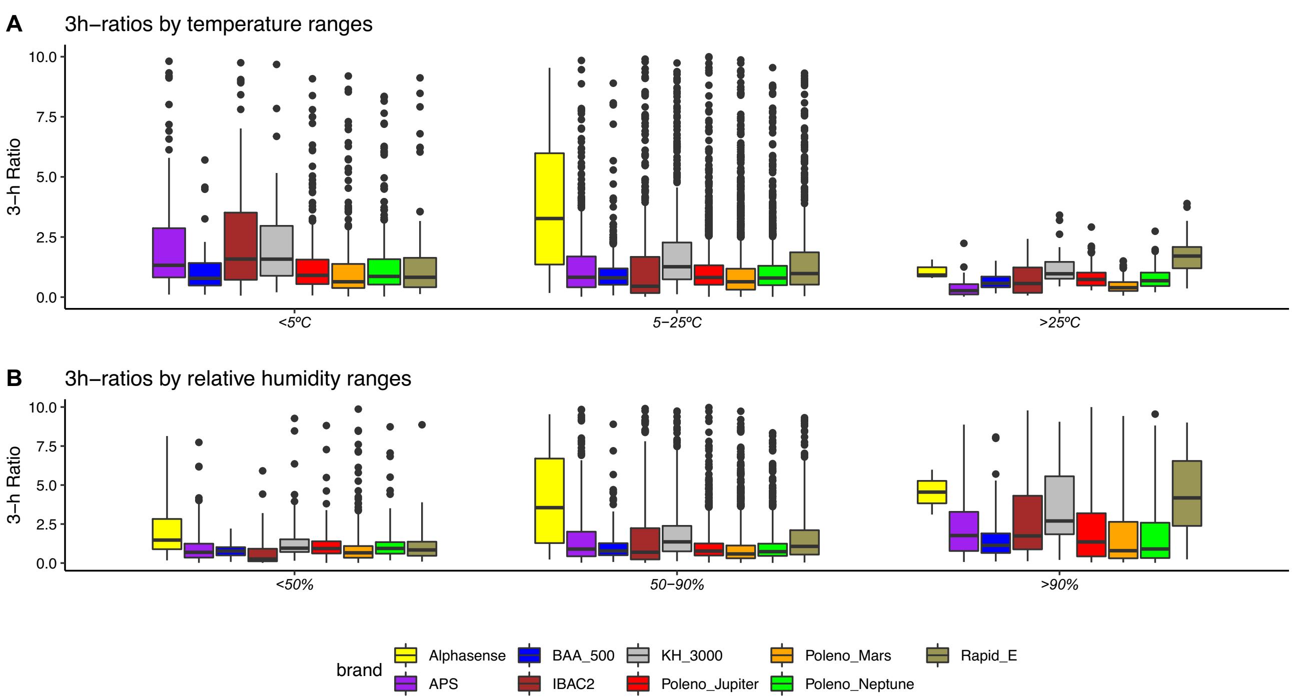

Fig. 7. 3-h ratios (from 0 and 10) between Hirst and automatic measurements of total pollen for different temperature (A) and relative humidity (B) ranges.

significantly impact the IBAC2, KH-3000, and some algorithms applied to the Poleno devices.

Algorithms applied to laser-based instruments were not able to distinguish between water droplets and pollen grains, when there was a high amount of rainfall. This was the case of IBAC, which explains the high correlation found with rainfall and relative humidity. Also, Poleno devices and Alphasense encountered this problem. Later works have improved such algorithms enabling the correct identification of water droplets. In the case of the Poleno systems, this issue was later addressed by adding raindrops as an additional category in the identification algorithm (https://www.knowledge.swisens.ch). In the case of Alphasense, the weather variables were included in the algorithms (Mills et al., 2023b). Similarly, the Rapid-E showed a bias with temperature, perhaps resulting from higher temperatures affecting the performance of the instrument's laser and in turn, the measurements.

These results suggest that environmental conditions (e.g., rain or high temperatures) are relevant parameters to include in some classification algorithms, that instruments need to be protected or algorithms adapted accordingly as shown by Mills et al. (2023b). It also indicates that real-time instruments can be expected to benefit from co-located environmental observations.

We found that the Hirst-type traps usually presented an average value when compared to the automatic devices for each environmental factor. It should not be forgotten that this value was the average of four traps, which might have shown different results if individual Hirst traps had been considered. Because Hirst-type traps have well-known limitations and present high variability (Oteros et al., 2017; Adamov et al., 2021; Suarez-Suarez et al., 2023), four Hirst traps were used during the campaign and the mean of their results was used as a baseline to compare with the automatic devices, to reduce the variability.

The BAA500, a system based on the same principle as the Hirst-type trap (i.e. impaction and image identification), showed similar correlations with environmental conditions than Hirst traps. Some of the algorithms applied to the Poleno Jupiter and Neptune devices also showed similar correlations with environmental conditions, despite their measurement technique being very different from the manual Hirst trap (Sauvageat et al., 2019). This indicates that the devices have similar sensitivities to environmental changes, which could be useful for comparing data from devices with such different measurement approaches. It could also indicate the intrinsic link between pollen concentration and environmental factors, thus providing confidence that certain instruments measure similar pollen concentrations even under different environmental conditions.

Table 3 provides a summary of the distance of the correlations of each instrument to the average of the four Hirst-type traps. As previously mentioned, we expected that instruments based on similar techniques would be grouped. Nevertheless, this was not the case for the APS, which we expected to behave more similarly to the Hirst-type traps since it is also a device that uses impaction and image identification (Jiang et al., 2022). This system suffered from relatively large errors for a number of pollen taxa (Maya-Manzano et al., 2023), so it is likely that this affected the results presented here.

A Poleno Jupiter system had the shortest averaged distance to the Hirst mean for the average of all variables considered (including both, weather and pollutants variables). The BAA500 showed the shortest distance for air temperature. The distance for wind speed was smaller for the APS, the Alphasense, and the Rapid-E. This is an interesting point since none of these instruments are oriented into the wind, and the airflow sucked into the instrument might not be strong enough to avoid the effect of wind, as is the case for the Poleno or the BAA500, which have much higher flow rates. The Rapid-E showed larger differences for the correlations with air pressure and temperature.

Considering the limitations of the manual method, measuring similar pollen concentrations might not actually be the optimal result for an automatic device. An example of this is the results observed in Fig. 7, where we can see a trend towards higher ratios during periods with low temperatures. As previously mentioned, this pattern suggests that the total pollen ratio is sensitive to temperature fluctuations or that the ratio is sensitive to low pollen concentrations, which usually occur during low-temperature periods. This ratio might also be impacted by the higher uncertainty of Hirst-based pollen concentrations <10 grains/m^3 (Adamov et al., 2021). However, the aim of this study was to evaluate the impact of weather and air quality parameters on the efficacy of capturing and identifying different pollen, not to determine the best-performing device.

Fig. 4 shows the difference in how weather variables and pollutants affected Hirst and automatic traps, expressed by the ratio between each automatic device and the Hirst. It is expected that some environmental conditions may impact the pollen concentrations measured more than other variables, which might itself introduce a bias in the analysis. For instance, temperature impacts the concentration of all taxa. However, it is also an indicator of the pollination season for the pollen types analysed here. *Betula* and *Fraxinus* pollinate in the early spring, when temperatures are still low. In contrast, *Poaceae* and *Quercus* pollen appear when temperatures are rising in the late spring (Fig. 6A). We observe different behaviour regarding temperature in the concentrations of *Betula* and *Fraxinus*, likely resulting from false positive classifications outside of the main pollen season (Fig. 5).

We did not identify high correlations between air pollutants and pollen concentrations, except for the limited differences during high levels of O_3 and PMs. Most likely the gaseous pollutants do not strongly react enough with the proteins of the pollen grains to induce observable differences, or maybe they did not have enough time to do so. It might happen that pollutants need more time to produce chemical changes in the surface of pollen grains, as has been found in other studies, although in laboratory conditions (Pöhlker et al., 2013). Such changes modify the emission spectra and may increase the errors in identification from systems relying heavily on fluorescence-based devices.

The correlation with O_3 follows the same pattern as temperature. This can be explained by the increased photochemical activity in the atmosphere during summer. It was expected that high levels of PM could also provoke differences in pollen concentrations between the different devices caused by misclassifications. When particles are attached to pollen grains, it prevents algorithms from properly recognizing the shape, for instance, in the case of holography-based instruments, or might occlude the pollen grains preventing their detection in image-based devices (Ren et al., 2016; González-Alonso et al., 2023). For the Alphasense, PM caused misclassifications because of their hygroscopic growth. This could be an explanation why it shows instability with high relative humidity values (Fig. 7). However, high levels of PM as cause of misclassification was not frequently observed, which is an important finding as the observation site in Munich can be considered representative for a major urbanised zone in Central Europe.

Although the AQ measurements applied in this study is from a background station, and should represent the regional level, it should be noted that the measurements are not co-located with the pollen campaign. Future studies on this, should consider measuring AQ at the same site.

Overall, correlations observed at daily and 3-hourly resolution between pollen concentrations and environmental factors were very similar, suggesting that this correlation behaves similarly in both seasonal and diurnal patterns. And therefore, showing similar values as for daily resolution correlations.

This study provides a comparative analysis of a large range of automatic pollen monitoring devices and their sensitivities to environmental conditions under real-world conditions. These insights could be useful for optimising these devices, improving their algorithms, and making better use of their data in different applications. Further research is needed to explore the impact of other environmental conditions on automatic instruments, to perform comparative analyses under different climatic conditions, and to understand the influence of specific local factors, such as extreme high or low temperatures, relative humidity or daily accumulated precipitation on pollen measurements. Future studies should also include comparative analyses under different climatic conditions, perhaps with multivariate analysis, such as PCA.

5. Conclusions

The automatic pollen monitoring devices assessed in this study generally demonstrated the ability to measure pollen concentrations in a manner comparable to the manual Hirst method under the environmental conditions encountered during the EUMETNET AutoPollen COST ADOPT intercomparison campaign 2021. Our results showed that most devices were similarly influenced by meteorological parameters and were able to provide good quality airborne pollen concentration data. However, there were notable differences among the devices, likely due to their different technical designs and the different algorithms applied, with some performing considerably better than others. These differences could be manifested as variations in correlation with environmental conditions, or as biases under certain conditions.

Notably, some devices showed substantial variability between the different algorithms applied, highlighting the importance of algorithm design in obtaining accurate measurements. We also observed potential biases in some devices under specific weather conditions, such as high temperature, high relative humidity, and during periods of rainfall. We did not find a significant influence of pollutants on pollen concentrations. This suggests that any impact from pollutants on overall measured pollen concentrations is either near the detection limit or requires longer exposure times to manifest. However this does not remove a potential impact from pollutant episodes (e.g very high PM) on the measured concentrations.

It is important to point out the limitations of the Hirst-type traps and the fact that obtaining similar pollen concentrations may not necessarily indicate optimal performance of an automatic device. However, the objective of this study was primarily to assess the impact of weather and air quality factors on the efficiency of the automatic devices in sampling and identifying pollen, not to rank the devices in terms of overall performance.

CRediT authorship contribution statement

M. González-Alonso: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **J. Oteros:** Writing – review & editing,

Writing – original draft, Visualization, Software, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **M. Widmann:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **J.M. Maya-Manzano:** Data collection, Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **C. Skjøth:** Writing – review & editing, Writing – original draft, Supervision. **L. Grewling:** Writing – review & editing, Data curation. **D. O'Connor:** Writing – review & editing, Data curation. **M. Sofiev:** Writing – review & editing, Data curation. **F. Tummon:** Writing – review & editing, Writing – original draft, Data curation. **B. Crouzy:** Writing – review & editing, Data curation. **B. Clot:** Writing – review & editing, Data curation. **J. Buters:** Writing – review & editing, Supervision, Data curation. **E. Kadantsev:** Writing – review & editing, Data curation, Conceptualization. **Y. Palamarchuk:** Writing – review & editing, Data curation. **M. Martinez-Bracero:** Writing – review & editing, Data curation. **F.D. Pope:** Writing – review & editing, Data curation. **S. Mills:** Writing – review & editing, Data curation. **B. Šikoparija:** Writing – review & editing, Data curation. **P. Matavulj:** Writing – review & editing, Data curation. **C.B. Schmidt-Weber:** Writing – review & editing, Data curation. **P.V. Ørby:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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