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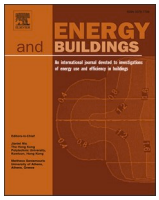

Assessing the performance of portable gas-phase air cleaners and Implications for their use in buildings

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ABSTRACT

We examined the performance of two different brands of gas-phase air cleaners using Proton Transfer Reaction Time-of-Flight Mass Spectrometry (PTR-ToF-MS) measurements; both air cleaners used activated carbon filters. The measurements were made in a typical office with furnishing and two occupants. The air cleaners were examined under multiple airflow settings and with different numbers of active units. The distinct non-negligible 44 mass-to-charge ratio (m/z) signals for ions representing various organic compounds or their fragments were identified by PTR-ToF-MS. Operation of air cleaners consistently reduced the magnitude of twenty-two of them. We analysed the decay of the m/z signals to characterize the performance of air cleaners in terms of their pollutant removal effect. We observed that it was different for the different m/z signals, suggesting different removal efficiencies for various compounds or their fragments. Removal efficiency decreased with higher airflow rates through the air cleaners though the rate of clean air delivered by them was higher. Our results document that describing the performance of gas-phase air cleaners must include reporting of removal effects for different organic compounds along with the clean air delivery rate. Alternatively, target compounds can be identified and their removal efficiencies reported together with the air cleaning effect. The present work describes the methodological approach that can guide the revision of current practice and standards for evaluating the performance of gas-phase air cleaners. More studies using this methodological framework can lead towards greater adoption and use of gas-phase air cleaners in sustainable and healthy buildings.

1. Introduction

We spend about 90 % of our lives indoors [1]. Indoor air pollutants influence the perception of indoor air quality (IAQ), health, work productivity, learning and sleep quality [2–8]. Organic compounds, including volatile organic compounds (VOCs), play a crucial role in determining indoor air quality [9–12]. These compounds can have both outdoor and indoor sources. The latter includes building materials, furniture, upholstery, and emissions from occupants (bioeffluents) [13,14]., as well as chemical reactions and transformations occurring indoors [15,16]. A variety of acute, non-clinical, building-related symptoms (sometimes referred collectively to as sick building syndrome, SBS), including agitation, irritation, nausea, vomiting, headaches and abdominal discomfort have been associated with the presence of organic pollutants [17,18]. Occupant perception of air quality in buildings, the so-called perceived air quality, predominantly depends on the presence of the organic compounds, and to some extent on thermal conditions as well [19]. In addition to guideline values for the allowable concentration of a few compounds, perceived air quality mainly serves as a foundation for deriving ventilation rates in most current ventilation standards and guidelines [20,21].

Relying solely on outdoor air ventilation to control the exposure to organic compounds indoors is energy demanding [22]. For example, in Japan, approximately 30 % of the energy used during building operation is attributed to heating, ventilation, and air-conditioning systems [23]. Reducing the sources of pollution is the most effective strategy [24] for improving IAQ without increasing the costs of used energy; however, this method cannot always be applied. Another method considered to reduce energy use while improving IAQ, similar to ventilation with outdoor air, is air cleaning. It can be achieved using different

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technologies, where air cleaners with sorbent materials have been observed to be among the most effective ones [25]. Activated carbon or other adsorption materials are used as sorbents in air cleaners which may be installed inside ventilation ducts, i.e., in-duct air cleaners [26,27], or placed in the rooms. The latter we call in the present work gas-phase portable air cleaners (GPACs) [28]. The sustained focus on air-cleaning technologies has been driven by desire to understand whether GPACs (and other air cleaners) can improve IAQ with the effect at least similar to what is achieved with outdoor air ventilation, and whether there is a net energy use benefit in this process [28]. This was one of the major objectives of Annex 78 established by the International Energy Agency [29].

The performance of GPACs can be evaluated by challenging them with air pollutants and examining their removal efficiencies. Knowing removal efficiency and the airflow through the air cleaner, the clean air delivered by the air cleaner can be calculated. Clean air delivery rate (CADR) is the flow rate of clean air delivered by air cleaner considered to be equivalent to the flow rate delivered by ventilation with outdoor, presumably clean air, i.e. devoid of the specific pollutants of concern [30–32].

Because of time and cost, the number of compounds used for such challenge studies during testing phase is limited. Typical evaluations focus on a small number of target compounds, often those suspected of having negative health effects, such as formaldehyde, benzene, xylene, and ethylbenzene [30]. The recent Appendix AA to ASHRAE Standard 62.1 lists the compounds considered to be relevant for health and comfort when ventilation is designed using the so-called indoor air quality procedure [33], where ventilation with outdoor air can be supplemented with air cleaning However, numerous other organic compounds and their mixtures can affect health and comfort, and can impact work performance, learning and sleep quality [5,6] even when they are present indoors at the very low concentrations. For many of these compounds, no systematic toxicity data are available. The lack of information on removal efficiency for these other, potentially relevant, pollutants is a limitation of the method at which the performance of GPACs is currently characterized and described [34–37]. Focusing on a small number of specific compounds during testing, albeit useful and necessary, may not be sufficiently representative when the performance of air cleaners is compared with ventilation that is considered to dilute and remove more, if not all, compounds.

The efficiency of GPACs in removing pollutants is generally characterised by one representative number, removal efficiency in % or predominantly CADR in air change rates per hour. These parameters are derived using the tests with challenge compounds, as described above. It is then frequently assumed that the GPAC will provide similar effect for other compounds without actual validation of this assumption. Because the removal efficiencies of GPACs can be different for various organic compounds, a proper documentation of this phenomenon is necessary to raise the awareness among building designers and operators as well as to improve the methods for testing of air cleaners and interpretation of the expected effects and measurements, before GPACs are widely used in practical applications. Information on removal efficiencies for all compounds examined during testing would provide better understanding of the actual performance of GPACs in buildings and consequently lead to more pertinent application of them. But it may not always be possible to derive such information. Additionally, it may be quite expensive to perform such analyses.

The reduction of a normalized concentration of organic compounds is often used to evaluate the performance of GPACs [34,38,39]. However, this approach has not been used consistently. Different initial concentrations of compounds and various airflow setting have been used, making it difficult to compare the parameters characterising air cleaners' performance [40,41]. To eliminate the influence of initial concentrations, CADR was derived from the concentration decay in the testing chambers with different volumes [31,32]. In the latest standard, the performance of GPACs has been expressed in terms of CADR, describing the flow rate necessary to reduce the concentration of target compounds when the GPAC is in operation [31,40,42–45].

Currently, there is no standardised protocol for characterizing CADR at a level detailed enough to understand the efficacy of a GPAC in an everyday environment, such as an office room; the available CADR do not even include all compounds that can cause harm. Several standards propose methods for measuring performance [40,43,45], e.g., AHAM AC-4–2022, GB/T 18801–2022, and IEC/CD 63086–2-2. These documents outline approaches to evaluate GPACs under laboratory conditions (e.g. inside the special chambers) for the removal of specific, target organic compounds (e.g., toluene and benzene). However, this leaves open the question of generalizability of the results obtained to other organic compounds and the plausible effect in an actual built environment. It neglects the potential differences in removal efficiencies among various organic compounds as well as under various operational scenarios.

Because of the complexities described above and limitations of applying analytical methods, sensory evaluations of the quality of air delivered by GPACs were proposed to characterize their performance [46–48]. A standard was recently accepted describing how the performance of GPACs should be evaluated using sensory evaluations of air quality [49] and partially validated in a few experiments [50,51]. Although this evaluation is very useful [52], it only addresses compounds that can be perceived (i.e. those eliciting sensory response such as odour or irritation) and does not provide the information on performance of GPAC for specific pollutants but rather for their mixture. These mixtures can be completely different in various built environments.

Proton Transfer Reaction Time-of-Flight Mass Spectrometry (PTR-ToF-MS) represents a significant advancement in mass spectrometry enabling real-time monitoring of organic compounds at concentrations as low as parts-per-trillion (ppt), with response times as fast as 0.5 s [53]. PTR-ToF-MS has been previously used in several studies to assess the performance of different air-cleaning technologies [31,32,39,48,54,55,56,57]. For example, Ye et al. and Fang et al. assessed the performance of different air-cleaning technologies by monitoring organic compounds in climate chambers [39,55]. Joo et al. and Kolarik et al. used PTR-MS to evaluate the performance of electronic and photocatalytic air cleaners in a simulated office environment [48,54]. Nie et al. reported the removal of organic compounds and energy consumption [56]. Sørensen et al. evaluated the removal effect of various organic compounds by different air-cleaning technologies [27]. A common result of these studies, particularly underlined by Sørensen et al. [32] and Schumacher et al. [57], was that removal efficiencies were different for various organic compounds indicating that the performance of GPACs cannot be characterised with a single parameter. However, no systematic studies were carried out with PTR-ToF-MS to improve the characterization of the performance of GPACs under different operational scenarios [58].

To leverage the potential of PTR-ToF-MS for real-time measurement of compounds to characterize the performance of GPACs, a standardised methodology is required. Such a methodology will allow comparisons across different studies, compounds and technologies. It will also enable building up a database with CADRs necessary for controlling levels of specific organic compounds in indoor environments. The methodology would also address the need for better understanding how operational scenarios such as GPAC airflow settings and the number of GPACs affect the removal efficiency and the CADR. This understanding can additionally provide input for recommendations regarding the application of GPACs in real buildings.

To address some of the needs and gaps in knowledge listed above, we performed measurements in a normally furnished office with two occupants where we systematically examined the performance of two brands of GPACs at multiple configurations. The performance was examined by monitoring the organic compounds in the office; he measurements were made with PTR-ToF-MS [59]. Our objective was to supplement the knowledge on the performance of GPACs particularly

focusing on two problems: (1) Can the performance of GPAC be characterised by a single parameter? and (2) Do different GPACs' configurations and airflows affect similarly the removal efficiencies for various compound?

2. Methods

2.1. Measuring site

The study was carried out in a 108 m^3 office (6 m × 6 m × 3 m) as shown in Fig. 1. The room did not have a mechanical ventilation system. The windows were consistently kept ajar (i.e. open with a 9 mm gap) during all the measurements performed, to provide ventilation with outdoor air.

The air change rate was measured several times using the decay of a tracer gas added to the room [60,61]. Freon 114 was used as the tracer gas and its concentration was measured by the Innova monitor 1302 with the Innova multipoint sampler 1303 (Innova Airtech Instruments A/S, accuracy: ±5 ppm) at 30-second intervals. The air change rate was calculated to be on average at 0.25 h^{-1}; This outdoor ventilation rate was assumed at the outset of experiments to be constant during measurements. It corresponded to 4 L/s per person with two occupants present, which is the base ventilation rate proposed by the HealthVent project when humans are the primary pollution source [61] and the pollutants listed by the World Health Organization's (WHO) Air Quality Guidelines [62–64] are at the levels at or below their guideline values. This rate per person is also part of the European Standard EN 16798 [60].

The room had hard floor covering (no carpet), five desks, and bookshelves. No pollution sources were intentionally added to the room during measurements. Two occupants engaged in regular office work stayed in the office during measurements (there were three occupants to build up the concentration of emissions from humans, see below) and left the room only for brief moments (restroom visits) during the measurements. The GPACs were placed in the centre of the office, while two occupants sat at the windows on one side of the operating GPACs.

The dry-bulb temperature and relative humidity were not controlled during the measurements, however the measurements showed that their fluctuations were relatively small: During all tested scenarios, the dry bulb temperature ranged between 21.0 and 23.8 °C, while the relative humidity varied between 50 % and 63 %. The dry bulb temperature and relative humidity were recorded using a data logger (HOBO U12-012, accuracy: ±0.35°C, ±2.5 %).

Concentration of carbon dioxide (CO_2) was measured using the Innova monitor 1302 with the Innova multipoint sampler 1303 (Innova Airtech Instruments A/S, accuracy: ±5 ppm). CO_2 concentration was relatively stable during measurements confirming that the outdoor air ventilation rates through the opening of the windows was relatively constant. Particulate matter was monitored using an optical particle sizer (TSI OPS 3330, accuracy: ±5-10 %), and ozone levels were recorded with an ozone monitor (2B Technologies Model 205, accuracy: ±2%). The measurements of temperature, relative humidity, CO_2, particulate matter, and ozone were taken at the centre of the office. The results of these measurements are included in the Supplementary Material (SM).

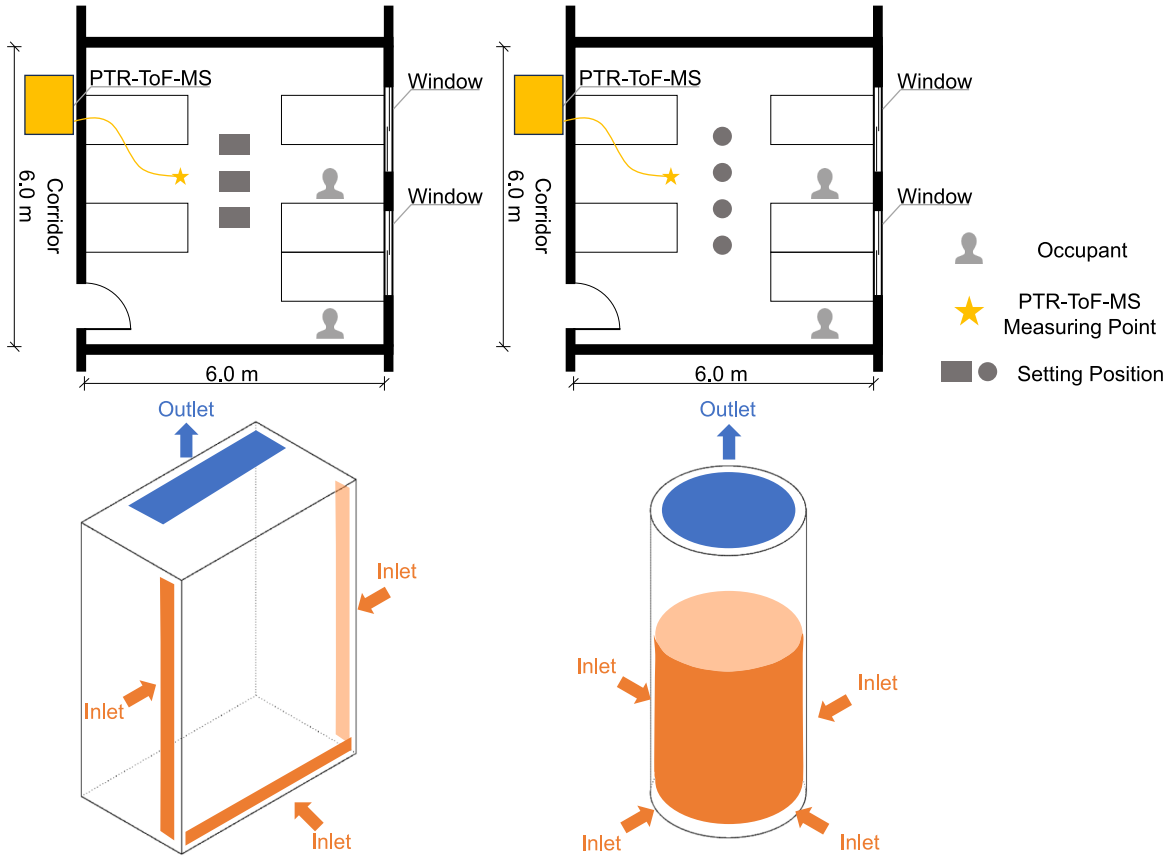

Fig. 1. The office where the measurements were carried out showing configuration and location of GPAC units and sampling point for PTR-ToF-MS. During experiments, one or three GPAC-1 units (shown below Fig. 1 left) were in operation or one or four GPAC-2 units (shown below Fig. 1 right). They were operated at different airflows (Table 2). Their location is illustrated in the figure. PTR-ToF-MS placed in the corridor adjacent to the office. The figure also shows the schematic diagram of GPAC-1 (left) and GPAC-2 (right).

2.2. Gas-phase air cleaners (GPACs)

GPACs from two manufacturers were used and named GPAC-1 and GPAC-2; they had similar filters and maximum airflow rates (Fig. 1 and Table 1). These GPACs were previously used in experiments to assess their effect on perceived air quality [51].

GPAC-1 had a maximum airflow rate of 510 m^3/h and consisted of four air-cleaning and separately installed layers: a pre-filter, HEPA filter, activated carbon filter, and a platinum catalytic filter. The platinum catalytic filter, advertised by the manufacturer as having ability to convert organic compounds, such as formaldehyde, into less harmful compounds, added an extra air-cleaning technology [65,66]; no electric charge was provided to the catalytic filter during the current study.

GPAC-2 had a maximum airflow rate of 520 m^3/h and consisted of three air-cleaning layers: a pre-filter, HEPA filter, and activated carbon filter combined into a single module.

Table 1 shows different operational modes of GPACs examined during the present measurements. For GPAC-1, Mode A, Mode B and Mode C corresponded to the airflow through the unit set at 103 m^3/h, 306 m^3/h, 510 m^3/h. For GPAC-2, Mode A, Mode B and Mode C corresponded to the airflow through the unit set at 60 m^3/h, 290 m^3/h, 520 m^3/h respectively. The airflow rates for each mode and brand were obtained from the manufacturers' datasheets and not verified by separate measurements in the present experiments.

Power consumption at each operational mode was measured for both brands using a socket power meter (SARTANO EMD-3, accuracy: ±1%). Measurements were taken over a 5-minute period with readings logged every second. The average power consumption was calculated for each mode.

3. Measurement scenarios

Eight scenarios were examined, in total, for GPAC-1 and GPAC-2 (Table 2). All carbon filter cartridges in GPACs were replaced with the new ones before the start of measurements. We used either one or three GPAC-1 units and one or four GPAC-2 units. Four units were used to ensure similar airflow delivered by GPAC-2 units as in the case of GPAC-1 units.

3.1. Measurement procedure

The chemical measurements were made with the PTR-ToF-MS. It was a custom-built instrument following a design that had been described in detail by Müller et al. [67]. It enabled real-time measurement of most VOCs with a temporal resolution of 1 Hz, resolving isobaric ions with a mass resolving power (m/Δm) of approx. 3000. The instrument's reaction chamber was operated at 60 °C, 3.75 mbar, and 700 V, resulting in a reduced electric field (E/N) strength of 93 Td, (1 Td = 10^{-21} V m^{-2}). The PTR-ToF-MS was operated in the H_3O^+ mode.

PTR-ToF-MS was calibrated using a gas calibration mixture (Apel-Riemer Environmental, USA) containing acetone at 1 ppm (±5%), among other organic compounds [67]. The acetone gas standard was introduced via a liquid calibration unit (LCU, Ionicon Analytik, Austria). This allowed dynamically diluting the standard with zero air and admixing HPLC-grade water into the gaseous calibration mixture to account for the change of sensitivity induced by the relative humidity changes.

The PTR-ToF-MS was placed outside of the room. The room air was sampled continuously at 2 L per min from the measurement point on the left side of the office (Fig. 1) through a 4 m 1/8″ PFA line heated to 50 °C. A fraction of this flow was subsampled into the PTR-ToF-MS analyser. The time-resolved signals for different *m/z* were continuously registered. The location of the sampling point was centrally in the room.

The measurements were made during three phases, as illustrated in Fig. 2, using *m/z* 101.06 as an example. In Phase 1, three occupants entered the office and remained there for at least 2 h to build up the level of bioeffluents. During this phase, GPACs were not operating. Immediately before Phase 2 commenced, one occupant left while two occupants stayed in the office during the remaining part of measurements. The GPACs were turned on and Phase 2 began. It lasted for about 2 to 3 h. Phase 3 was a continuation of Phase 2; in this phase the measurement scenario was changed by altering the operational mode of the GPACs or adjusting the number of units in use. Table 2 describes all configurations tested on different days.

While the departure of one occupant at the start of Phase 2 could be expected to reduce the concentration of bioeffluents, the CO_2 measurements presented in the Supplementary Material confirmed that a person leaving the room at the end of Phase 1 did not disturb the equilibrium; the concentration in Phase 2 remained at the level similar to the one at the end of Phase 1.

3.2. Analyses

In the present analysis the *m/z* signals were assigned acetone-equivalent volume mixing ratios based on the acetone sensitivity from gas standard calibration. A relatively low E/N of approx. 100 Td was used, which limited fragmentation. The humidity (assessed based on the relative abundance of the hydronium ion-water cluster at *m/z* 55) was low, making clustering less of a concern. Still, even at this relatively low E/N we could expect non-negligible fragmentation of major indoor VOCs such as e.g. acetic acid.

Ion-molecule collision theory was not used to estimate the sensitivities. Instead, all the monitored signals were assigned acetone-equivalent sensitivity, based on the calibration for acetone in the gas standard. Acetone has a k-rate of ~ 3.4 (1^{-9} cm^3/s) at E/N of 100 Td, and since most VOCs that can be quantified using PTR-ToF-MS have k-rates in the range of ~ 2 – ~4.5, this puts it near the median.

The assignment of compounds to signals based on the parent ion mass is not straightforward. This does not hold true for some main indoor organic compounds such as ethanol or, particularly, formaldehyde. Consequently, the *m/z* = 31 signal corresponding to the parent ion of formaldehyde is prone to interference and suffers from low sensitivity. Still, its relative changes in an environment with stable RH might be indicative of relative changes in formaldehyde concentration.

The measured mass spectra ranged from *m/z* 14 to *m/z* 500, integrated every 5 s. The monitored signals were selected based on a signal-to-noise ratio threshold of approximately 20:1. They were then assigned to organic compounds based on the exact *m/z*. This assignment is tentative in nature because PTR-ToF-MS is a direct, soft-ionisation-based technique which is not ideal for qualitative analysis. The concentrations of the compounds tentatively assigned to the monitored ions were calculated using volume mixing ratios. A volume mixing ratio is a measure of concentration that expresses the quantity of a gas as a proportion of the total volume (e.g., ppbv, parts per billion by volume), and it is a convenient metric as it is independent of temperature and pressure. In this study, the volume mixing ratios of the compounds tentatively assigned to the monitored ions were calculated using acetone sensitivity as a proxy. This approach allows in the most cases to achieve

Table 1
Airflow rates and power consumption per unit for different operational modes of the GPACs.

GPAC	Operational Mode	Airflow Rate per unit (Q) provided by producer [m^3/h]	Power Consumption per unit (*P*) measured in experiments [W]
GPAC-1	A	103	5.7
	B	306	22.7
	C	510	79.5
GPAC-2	A	60	5.6
	B	290	16.1
	C	520	52.4

Table 2
Total airflow rate and power consumption of GPACs in the different operational configurations; Phases are explained in Fig. 3.

Configurations	Measuring day & phase	GPAC	Operational mode	Number of units	Nominal airflow rate per unit provided by manufacturer [m^3/h]	Total airflow rate provided by all used GPACs [m^3/h]	Total measured power consumption (P_t) [W]
1–1	Day 1, Phase 2	GPAC-1	B	1	306	306	22.7
1–2	Day 1, Phase 3		B	3	306	918	68.1
1–3	Day 3, Phase 2		A	3	103	306	17.1
1–4	Day 3, Phase 3		C	3	510	1530	238.5
2–1	Day 2, Phase 2	GPAC-2	B	1	290	290	16.1
2–2	Day 2, Phase 3		B	4	290	1160	61.4
2–3	Day 4, Phase 2		A	4	60	240	16.8
2–4	Day 4, Phase 3		C	4	520	2080	209.6

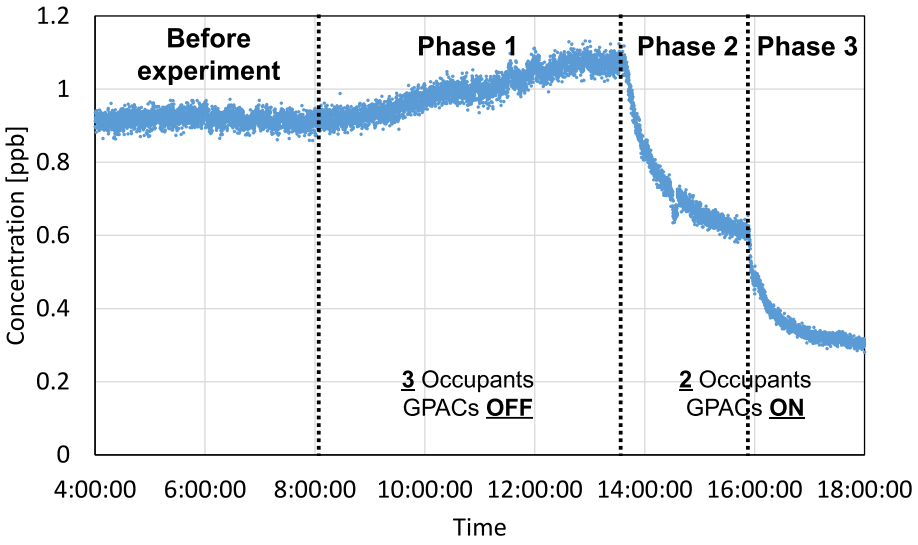

Fig. 2. Illustration of three phases during which the measurements were made. The figure shows the change in *m/z* 101.06 with time (data from measurements performed on **Day 4,** Table 2).

an accuracy of ± 40 % and leverages direct calibration. The sensitivity to acetone was determined based on a gas standard mixture (Apel-Riemer Environmental, USA).

During Phases 2 and 3 (Fig. 2), the concentration decay of the organic compounds from the PTR-ToF-MS measurements was determined using a numerical solution to the mass balance model [68]. A numerical curve-fitting method (nonlinear, least squares fit) was implemented, using a Python script [69]. This method allowed obtaining the decay rate for *m/z* signals (k_{decay}). The numerical solution used Levenberg-Marquardt algorithm, balancing gradient descent and Newton's method for optimization. It should be noted that albeit similar, the above procedure did not exactly follow the method for estimating the CADR for particulate air cleaners [40,43,45].It was not either the objective of the present work to perform measurements exactly following the standards as our interest was in understanding the changes in performance under different scenarios rather than precise derivation of removal efficiencies and CADR.

A trend analysis was then conducted (**Table S5 and S6** in the SI) to determine if the *m/z* signals decayed when the GPACs were in operation. If decay was observed, it was likely that the compounds associated with *m/z* signals were removed by the GPACs and for them the actual decay rates (k_{decay}) were calculated. The coefficient of determination (R^2) of the fitted decay curve was also calculated; an R^2 value of over 0.9 indicated that the fitted curve explained 90 % or more of the variance in the data. The *m/z* signals for which the fitted curve had an R^2 below 0.9 were eliminated from further analysis. This decision was arbitrary to include only the results where the fitting was considered to have a high precision, The process described above is illustrated in Fig. 3 and further details are provided in the Supplementary Material.

The decay rate (k_{decay}) includes the removal effect provided by GPAC (s) (in air change rates, RE_{ach}), by the ventilation through windows (estimated to be around 0.25 h^{-1}), and through all other losses in the space (e.g. to surfaces). These other losses could not be accounted for when estimating the "true" effect of GPAC. We assumed that all losses in the office space where the measurements were made similar during different operating scenarios of GPACs, which seems to be reasonable, and the losses to surfaces were negligible.

The differences in k_{decay} can thus be considered as representing the differences in performance of GPACs in terms of removal effects of organic compounds under various operation modes. To compare these removal effects with the airflows provided by GPACs, the outdoor air ventilation rate was assumed as a constant value (0.25 h^{-1}) and subtracted to get the removal effect in air change per hour (RE_{ach}). Then the resulting air change rate (RE_{ach}) was multiplied by the room volume (108 m^3). The result is a removal effect in m3/h ($RE_{m3/h}$) and it was calculated for each *m/z* for which the signal was detected, and the determined decay rate was reliable (as described above, based on R^2 values).

As mentioned above, both RE_{ach} and $RE_{m3/h}$ are proxies for CADR provided by GPACs. To estimate the removal efficiency ($REff_{\%}$), we divided $RE_{m3/h}$ by the airflow through GPACs; these airflows are taken as the values provided by the manufacturers and are shown in Table 1. We also calculated the energy efficiency ratio (EER) which compared $RE_{m3/h}$ and the total energy consumption (P_t), by dividing the former by the latter.

Linear mixed effects models were used to compare the effects of the

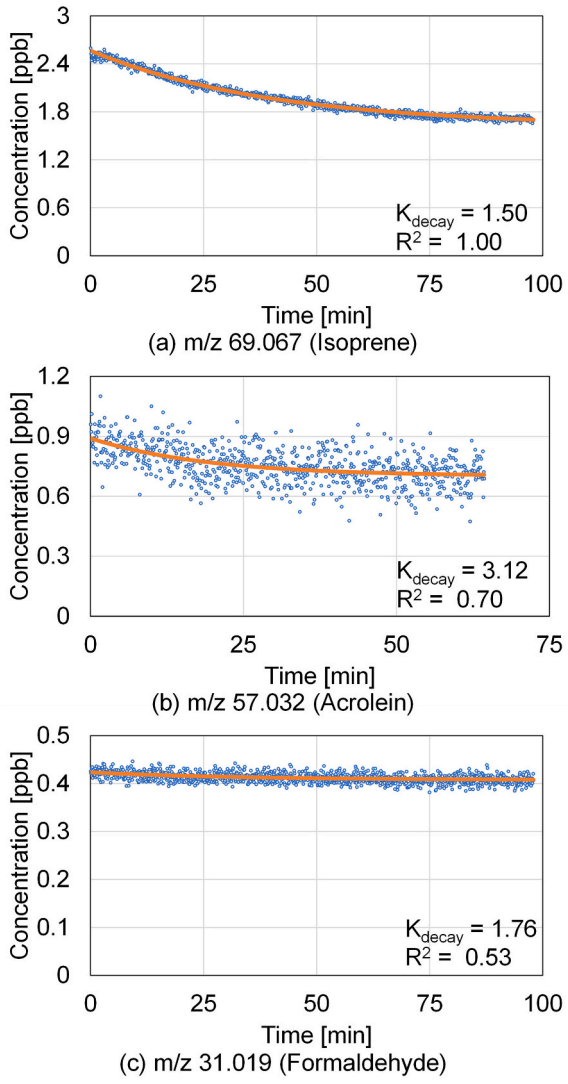

Fig. 3. An example showing the process of identifying *m/z* signals which decayed when GPACs were in operation. The data shown are for GPAC-2 in configuration 2–3 (Table 2). We selected *m/z* 69.067 (Fig. 3a, top), eliminated *m/z* 57.032 (Fig. 3b, middle) and *m/z* 31.019 (Fig. 3c, bottom). Raw data are in blue, and the fitted curve is in orange.

following variables: GPAC brand (GPAC-1 or GPAC-2), number of units (1 vs. 3 or 4), and airflow rate (variable by value); the details have been provided in the Supplementary Material.

4. Results

4.1. Removal effect

Twenty-two *m/z* signals were selected among 44 detected for estimating k_{decay} and $RE_{m3/h}$; they are shown in Table 3, where the compounds that are potentially associated with these *m/z* signals are listed. The formulae were matched with the compounds reported in previous field studies measuring organic compounds [27,51,70–73]. The reported signals can also include other compound fragments, and the assigned compounds are tentative.

The removal effects presented in Table 3 are plotted in Fig. 4 against *m/z*'s; no clear trend was noted for either GPAC.

4.2. Removal efficiency

In Fig. 5, the removal effects presented in Table 3 are plotted against the airflow delivered by GPACs. The red diagonal line represents the condition in which $RE_{m3/h}$ equals the airflow provided by GPACs, i.e. when a removal efficiency of 100 % is implied. Since all data points are below this diagonal, the results indicate that the removal efficiencies were lower than 100 %.

4.3. Comparison of removal effect and removal efficiencies

Removal effects ($RE_{m3/h}$) in m^3/h were plotted against different operation modes in Fig. 6. Removal effect increases as the airflow through the GPAC increases, particularly when comparing a single unit to multiple units working together. Whether one or several units are used, the same total airflow through the GPACs produces similar $RE_{m3/h}$.

Removal efficiencies ($REff_{\%}$) are presented in Fig. 7 for different scenarios from the present measurements. Notable discrepancies in $REff_{\%}$ across different *m/z* signals indicate that the performance of GPAC cannot be fully described by a single parameter describing its performance. Furthermore, removal efficiencies decrease significantly with an increase in airflow through the GPACs. Consequently, increasing the total airflow rate through the GPACs reduced $REff_{\%}$ suggesting that further increases in airflow would not be economically justified because they do not yield a significantly higher $RE_{m3/h}$. When the data for multiple units was compared, it can be seen that increasing total airflow by adding air cleaning units did not improve the $RE_{m3/h}$ (Fig. 6) probably due to the reduction in $REff_{\%}$ (Fig. 7).

We compared the relative contribution of each factor (GPAC brand, airflow per unit, number of units) to the predicted value of each performance indicator (Removal effect and Removal efficiency) using the standardised coefficients derived from the linear mixed-effects models. These values are summarised in Table 4 where values closer to one indicate a strong positive contribution and values closer to minus one indicates a strong negative contribution. For $RE_{m3/h}$ and $REff_{\%}$, the GPAC brand was the dominant factor. The airflow provided by the GPAC unit was nearly as important as that of the GPAC brand in predicting the $REff_{\%}$. While all the coefficients were positive for $RE_{m3/h}$, the coefficients for airflow per unit and number of units were negative for $REff_{\%}$. These results suggest that adding more units or increasing the airflow delivered by them improved the $RE_{m3/h}$ but reduced the $REff_{\%}$. This is also illustrated in Fig. 6 and Fig. 7.

4.4. Energy efficiency ratio

We also estimated the energy use under different scenarios and the full details of these calculations are provided in the Supplementary Material. Energy efficiency ratio (EER), i.e. the effect in m^3/h per energy use, is presented in Fig. 8 for different scenarios examined in the present measurements. Fig. 8 shows large differences in EER among almost all examined scenarios.

Additional results, including the calculated removal efficiency ($REff_{\%}$) and energy, are shown in SI (**Fig.S3 and S4**).

5. Discussion

5.1. Overall discussion of the results

The first question we sought to answer concerned the performance of GPAC and whether it can be characterized by a single parameter. The present results suggest that a single performance parameter cannot characterize a GPAC's performance. The results clearly demonstrate that removal effects differ for different organic compounds and one parameter or metric cannot universally characterize the performance of GPAC across the full spectrum of organic compounds. This is clearly demonstrated in Fig. 6 and Table 3. They reveal considerable variability in the

Table 3
Estimated removal effects in m^3/h ($RE_{m3/h}$) for selected *m/z* signals; N/A indicates that $RE_{m3/h}$ was below zero, potentially because of fluctuations caused by uncontrollable indoor or outdoor factors which introduced significant errors in the calculated k_{decay}.

Day		1	1	3	3	2	2	4	4
Number of Units		1	3	3	3	1	4	4	4
Total Airflow Rate provided by GPACs from manufacturer data [m^3/h]		306	918	306	1530	290	1160	240	2080
Operational Mode	Potentially associated organic compound (the signals can also include fragments of other compounds)	B	B	A	C	B	B	A	C
Brand			GPAC-1				GPAC-2		
m/z (Protonized compounds)		Removal effect, $RE_{m3/h}$ [m^3/h]							
59.048	Acetone	N/A	131	125	535	151	304	174	472
61.028	Acetic acid	N/A	292	144	156	240	414	225	433
69.067	Isoprene	35	138	136	199	135	299	143	310
71.048	Crotonaldehyde	50	149	144	195	134	299	172	331
73.062	2-Butanone (MEK)	40	105	77	223	142	324	171	312
75.042	Propanoic acid	165	224	137	151	180	343	187	344
79.038	Benzene	208	245	99	127	207	376	191	393
83.084	Cyclohexene	75	167	167	238	122	278	183	277
87.044	Methyl acrylate	85	188	189	194	180	313	209	295
87.078	2-Pentanone	85	155	135	152	115	319	156	318
89.058	Butyric acid	76	195	200	269	256	321	238	295
97.028	2-furancarboxaldehyde	94	178	186	214	163	280	184	267
101.06	Acetylacetone	103	179	168	282	184	272	189	282
101.092	n-Hexanal	93	175	111	163	107	295	151	344
107.051	Benzaldehyde	109	159	96	152	124	275	141	277
115.109	n-Heptanal	112	174	120	185	111	280	146	321
117.088	n-Butyl acetate	N/A	281	213	133	174	279	172	225
127.11	6-MHO	140	206	133	182	142	275	190	286
129.123	Octanal	108	196	139	162	131	275	165	282
137.131	Monoterpene	79	99	N/A	134	191	583	127	412
143.137	n-Nonanal	146	200	130	166	146	276	165	276
157.153	n-Decanal	210	225	135	167	149	270	180	270

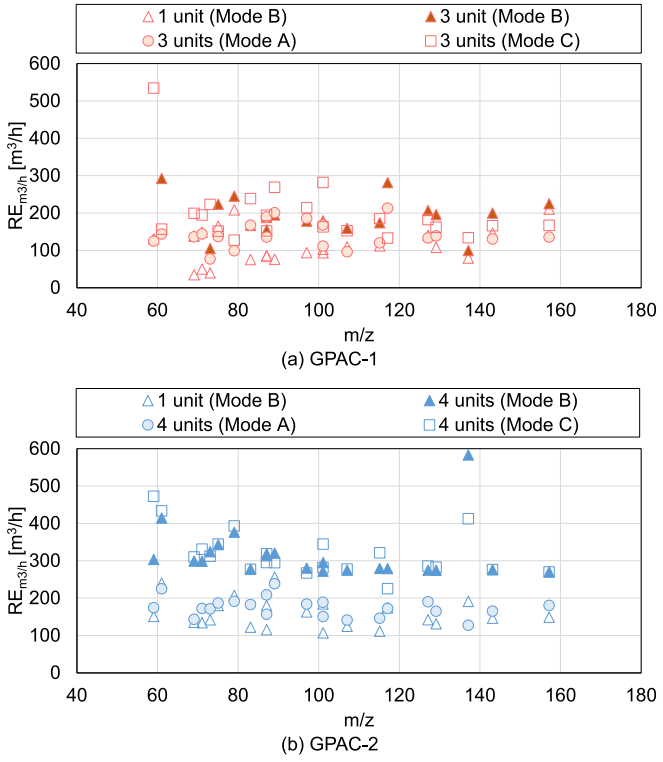

Fig. 4. Removal effects ($RE_{m3/h}$) as a function of *m/z* for GPAC-1 (a) and GPAC-2 (b).

removal rates for different compounds. For instance, when a single GPAC-1 unit was operated in Mode B, the estimated removal effect ($RE_{m3/h}$) for Isoprene was only 35 m^3/h, whereas the value for n-Decanal reached 210 m^3/h, showcasing the wide range of performance for different compounds under identical operating conditions. In addition to that, among 44 *m/z* signals detected by the PTR-ToF-MS, the operation of GPACs reliably reduced the levels for only 22. Thus, the GPACs examined in the present experiments did not universally remove all organic compounds, as is expected when ventilation with outdoor air is in operation. It may thus be concluded that relying on a single or a limited set of removal rates for selected pollutants, as for example prescribed by current standards (AHAM AC-4–2022, GB/T 18801–2022, IEC/CD 63086–2-2), fails to capture the full complexity of GPAC performance for use indoors. Consequently, the unequivocal conclusion is that using GPACs cannot completely replace ventilation and do not provide the effect equivalent with the effect expected when ventilation is in place. Their effect on IAQ should not be equated with the effect of ventilation at face value. These observations, however, do not dismiss the use and potential positive effects of GPACs for IAQ. When used as supplement to ventilation and for the specific target compounds for which the effective removal rates are carefully determined, they can potentially provide considerable benefits both to occupants in terms of the effects on health and comfort, and the system in terms of reduced energy use. This approach is entertained in the ASHRAE Standard 62.1 when indoor air quality procedure is used to determine the required ventilation rates [33].

The second question that we tried to answer concerned different configurations of GPACs and airflows through GPACs, and whether they similarly affect the removal efficiencies for various compounds. We found that the effect of increasing flow rate through GPAC or using additional GPAC units cannot produce a sufficiently strong change in

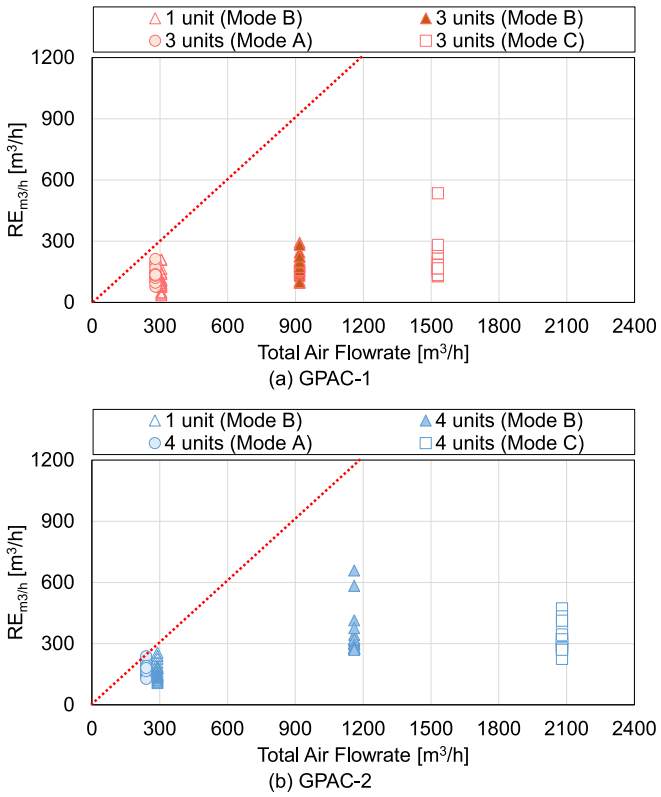

Fig. 5. Removal effect ($RE_{m3/h}$) as a function of the airflow provided by GPAC-1 (a) and GPAC-2 (b); each point represents $RE_{m3/h}$ for one m/z value, The red dashed diagonal line represents the condition where the removal effect equals the total airflow rate, implying a 100% removal efficiency.

removal of organic compounds. This observation is counterintuitive to what is generally expected. In the present experiments, it was observed that these actions increased the effective removal rate, but the change was not proportional to the increased flow. Removal efficiency decreased with increasing airflow through GPAC. This is highlighted when comparing the performance of three GPAC-1 units: as the operational setting was changed from Mode A (total airflow: 306 m3/h) to Mode C (total airflow: 1530 m3/h), the median removal efficiency across the measured compounds dropped from approximately 50 % to 12 %. These effects are clearly demonstrated in Figs. 6 and 7. They could plausibly be caused by the reduced residence time on the activated carbon filters. Future studies are necessary to elucidate further the underlying mechanisms.

Additional GPAC units did not result in a proportional increase of the removal rate which somewhat contradicts the conventional expectation. One of the reasons for this result could be caused by the experimental setup, wherein all GPAC units were in a close proximity (Fig. 2**).** Such spatial arrangement could result in the clean air discharged from one GPAC being inadvertently drawn into adjacent units, thereby reducing the overall removal effect. But there could be also other reasons for this result. Further studies are necessary to examine the optimal setup of GPAC units within the space for achieving the highest effect.

The initial increases in total airflow led to an increase in removal rate. However, soon this effect reached a plateau. Further increases in airflow subsequently led to very small changes in removal rates (Fig. 5) as declining removal efficiency offset the gains from increased airflow. Moreover, the energy efficiency of the GPACs decreased with higher airflow rates without corresponding improvements in the overall efficiency (Fig. 8). This result shows that besides evaluation of the removal efficiency the performance of GPAC should additionally consider estimation of energy costs as proposed by Bogatu et al. [74,75].

It is typically anticipated that the surface area of activated carbon filter would affect removal efficiency. However, no significant differences were seen between multiple units operating in Mode A (low airflow) and a single unit operating in Mode B (medium airflow). These configurations had similar total airflow rates but differed in the number of units (and consequently in the total surface area of the activated carbon filters). This suggests that the airflow rate, rather than the surface area alone, was a more important factor in determining the removal efficiency, at least in the present measurements.

The present study showed that nearly all compounds with m/z values above 59.048, corresponding to compounds with molecular weights greater than that of acetone and emitted by humans which are expected to impact the perceived air quality, were effectively removed. These findings suggest that our GPACs equipped with activated carbon were particularly effective at targeting compounds with molecular mass over a certain range. In contrast, as shown in **Table S5 and S6**, the removal efficiency for compounds with m/z below 59.048 was less predictable. Further studies are necessary to investigate how removal of a broader range of organic compounds from indoor air, including several of which are compounds of concern, affects perceived air quality and health outcomes [51] when using GPACs with activated carbon filter.

The present study did not intend to compare the two GPAC brands. However, it is clear from the present results that their performance differed significantly even though both used similar air-cleaning technologies (Table 5). This may be due to structural differences between the two brands [76,77]. The differences in removal efficiencies between the two GPAC brands were particularly evident for m/z values below 57.032 corresponding to compounds smaller than acrolein. Hence, even if two GPACs may use the same air cleaning technology and have similar flow rates, and may be characterized with the same performance parameters, design differences can cause that their performance, in terms of removal efficiency, to differ. Hence, their application should not be generalized. We refrain though from making broader generalisations regarding these observations.

The removal of specific target compounds can be determined for a GPAC. Such a methodology would align with the Indoor Air Quality Procedure outlined in ASHRAE Standard 62.1 [33]. This procedure would allow selecting the compounds with documented effects on occupants and the adaptation of ventilation strategies when air cleaning is employed. The limitation of this method is that while the odour threshold list by Nagata et al. [78] and the Appendix AA of ASHRAE Standard 62.1[33] define certain target compounds, the actual compounds present in indoor environments can be widely different. Additionally, there are multiple organic compounds in indoor environment which may be effectively removed by a GPAC, whose impact on occupant health and well-being have not been studied.

Table 6 presents removal efficiencies ($REff_{\%}$) for selected compounds. Two of these—benzene and acetone—are also included in Appendix AA of ASHRAE Standard 62.1 listing the compounds to be examined when employing air cleaning and the Indoor Air Quality Procedure [33]. Eight other compounds—acetic acid, isoprene, crotonaldehyde, 2-butanone, propanoic acid, benzene, 2-pentanone, and butyric acid—have low odour thresholds as reported by Nagata et al. [78]. All of these compounds were effectively removed by the GPACs in almost all operational scenarios in the present measurements.

Our result can be compared to other research on removal effect (m^3/h) and removal efficiency (%). Rajapakse et al [79] evaluated a GPAC unit with an airflow rate of 221 m^3/h in a controlled chamber of 12.68 m^3 (dry bulb temperature = 21.4–22.2 °C; relative humidity = 46–53 %) using solid-phase microextraction-gas chromatography mass spectrometry (SPME-GC–MS). They calculated the removal efficiencies for nine bioeffluents, including 2-butanone, benzene, and toluene, which ranged from 23.2 % to 61.2 %, with a median of 36.8 %. Blondeau et al. [27] assessed the removal effectiveness of a central ventilation system for offices and commercial buildings equipped with in-duct activated carbon filters using ion molecule reaction mass spectrometry (IMR-MS).

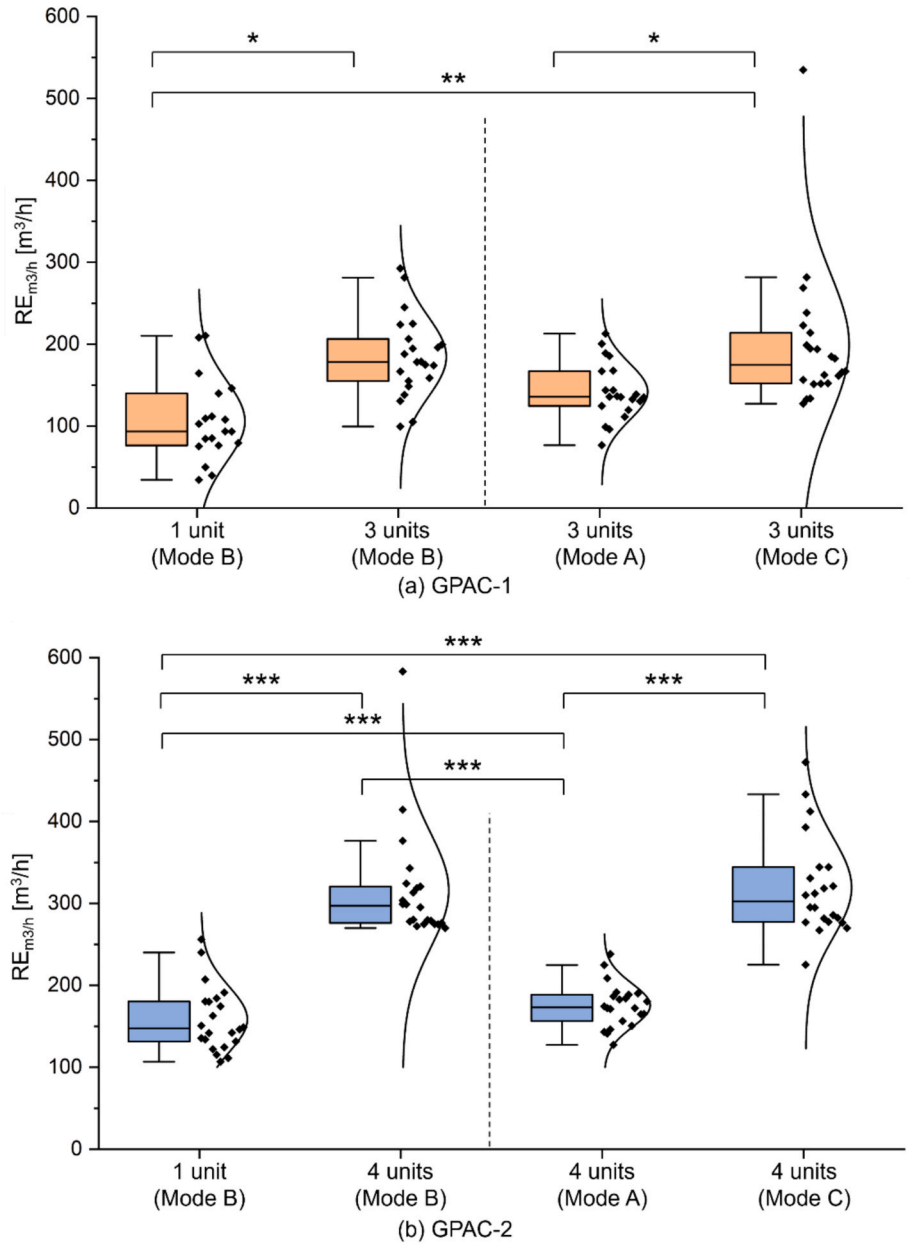

Fig. 6. Boxplots and probability density curves illustrating removal effect ($RE_{m3/h}$) for GPAC-1 (a) and GPAC-2 (b) under different scenarios simulated in the present measurements. The boxes represent the 25th to 75th percentiles, with the horizontal line indicating the median; the whiskers extend to the 5th and 95th percentiles. Each point in the overlaid curve to the right of each boxplot showing the probability density represents the removal effect for a single *m/z* value. Asterisks show whether differences between different scenarios were statistically significant, where *: shows $p < 0.05$, ** show $p < 0.01$, and *** show $p < 0.001$).

Their study reported removal efficiencies for acetaldehyde, acetone, heptane, toluene, and formaldehyde ranging from 22 % to 90 %, at an airflow rate of 1600 m^3/h in a simulated winter environment (dry bulb temperature = 19 °C; relative humidity = 45 %). By comparison, for the twenty-two *m/z* signals in the present study, GPAC-1 (1 unit, Mode B) achieved removal efficiencies ranging from 11.3 % to 68.8 % with a median of 30.6 %, and GPAC-2 (1 unit, Mode B) achieved removal efficiencies of 36.8 % to 88.3 % with a median of 50.9 %. The discrepancies between the present results and the other studies may be attributed to the assessment methods of GPAC performance which were carried out in the actual office environment in the present experiments, whereas the other studies were conducted in a controlled laboratory space. Additionally, the present study did not account for all removal mechanisms. Consequently, developing standard methods for assessing GPAC removal efficiency is an important requirement.

A key implication of the present work is that the current standards and testing protocols [40,42–45] may be inadequate for appropriately characterizing GPACs for real-world use. This becomes especially important when GPACs may be considered as an alternative to outdoor air ventilation. Air cleaner testing is typically conducted in laboratory settings, which may not accurately reflect field performance. The recent ASHRAE Position Document on Air Filtration and Cleaning [80] also highlights this issue and calls for the verification of laboratory test results in the real-world environments.

5.2. Limitations

One limitation of the present study is that the measurements were conducted at only one outdoor air supply rate. Also, the outdoor ventilation rate through the window could fluctuate daily due to

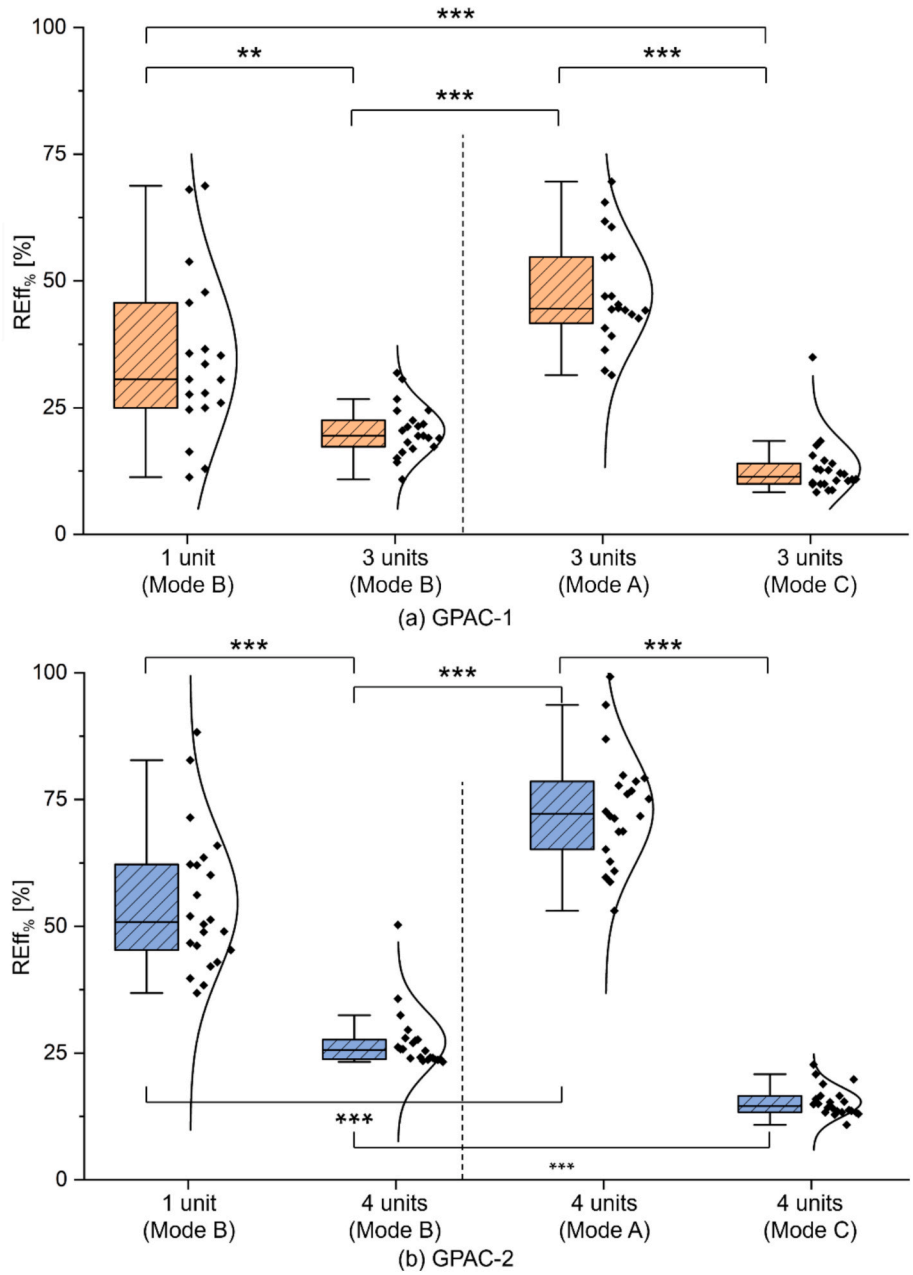

Fig. 7. Boxplots and probability density curves illustrating removal efficiency ($REff_{\%}$) for GPAC-1 (a) and GPAC-2 (b) under different scenarios simulated in the present measurements. The boxes represent the 25th to 75th percentiles, with the horizontal line indicating the median; the whiskers extend to the 5th and 95th percentiles. Each point in the overlaid curve to the right of each boxplot showing the probability density represents the removal efficiency for a single m/z value. Asterisks show whether differences between different scenarios were statistically significant, where *: shows $p < 0.05$, ** show $p < 0.01$, and *** show $p < 0.001$).

Table 4
The standardized coefficients from the linear mixed effects models between two GPAC brands for $RE_{m3/h}$, $REff_{\%}$.

	Standardized coefficients of fixed effects (in decreasing order)		
Removal effect ($RE_{m3/h}$)	GPAC brand (0.66)	Number of units (0.40)	Airflow rate per unit (0.38)
Removal efficiency ($REff_{\%}$)	GPAC brand (0.68)	Airflow rate per unit (−0.66)	Number of units (−0.29)

temperature, pressure, and wind conditions. The calculated removal effects could include errors due to fluctuations in the ventilation rate. However, the CO_2 concentrations measured during each study day (**Fig. S1**) show that the impact of ventilation through windows on the estimated removal effects was relatively small.

Validating the results by repeating the same scenarios and performing multiple measurements would have strengthened our findings. Additional verification of the observed results would be provided by investigating whether the same compounds were consistently removed with the same efficacy and at the same rate. However, owing to time constraints and limited access to the PTR-ToF-MS equipment, repetition of the experiment was not possible. Some validation was, however, obtained by running different scenarios showing that the same m/z signals were reduced by each specific brand of GPAC operating in different scenarios.

We did not perform measurements in an unoccupied room with the GPACs idled to determine the losses to the surfaces. We assumed that

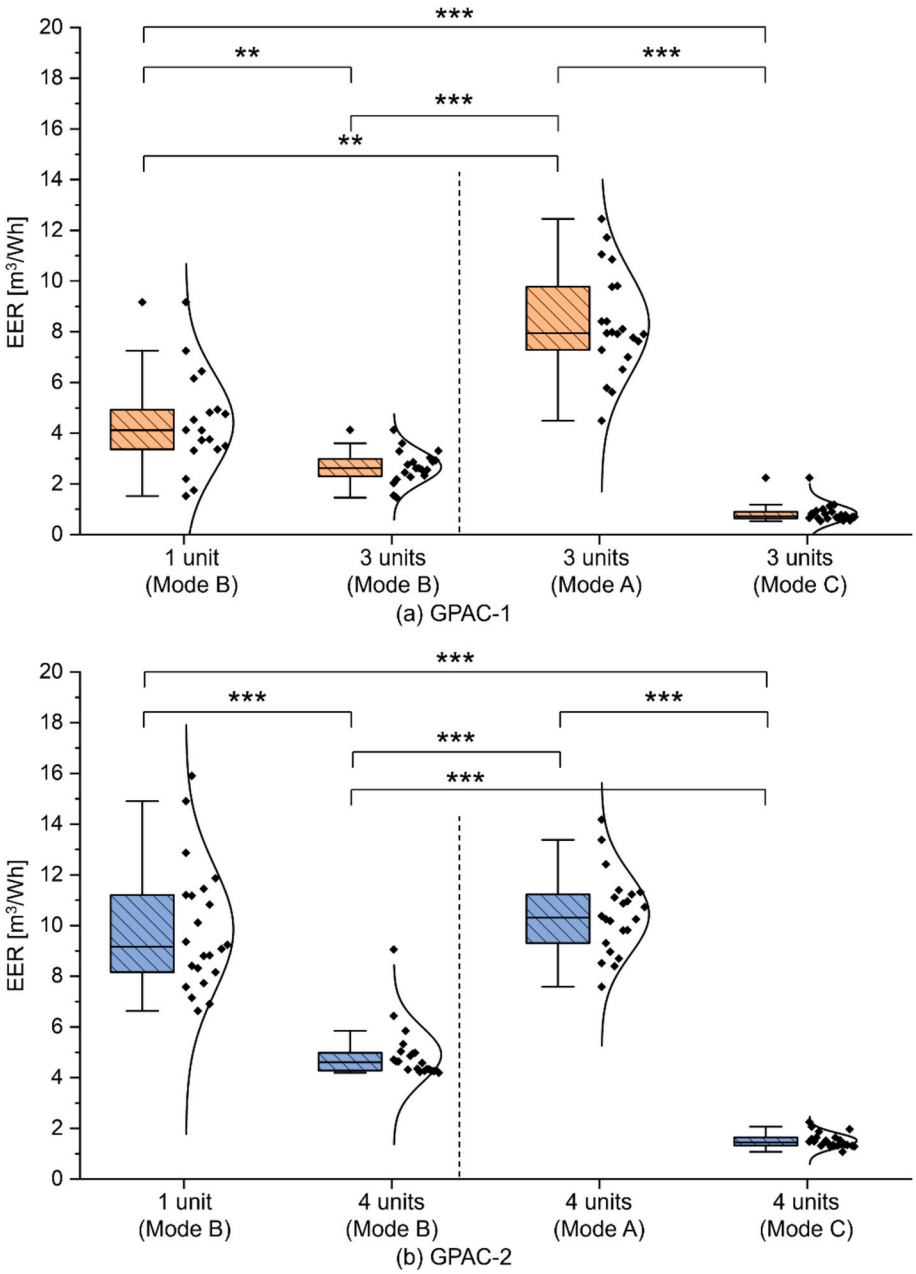

Fig. 8. Boxplots and probability density curves illustrating energy efficiency ratio (EER) for GPAC-1 (a) and GPAC-2 (b) under different scenarios simulated in the present measurements. The boxes represent the 25th to 75th percentiles, with the horizontal line indicating the median; the whiskers extend to the 5th and 95th percentiles. Each point in the overlaid curve to the right of each boxplot showing the probability density represents the energy efficiency ratio for a single *m/z* value. Asterisks show whether differences between different scenarios were statistically significant, where *: shows $p < 0.05$, ** show $p < 0.01$, and *** show $p < 0.001$).

Table 5
pairwise comparisons between the two GPAC brands based on the least-squares means of the linear mixed-effects model; The difference between the two brands was significant, with the GPAC-2 outperforming the GPAC-1 in all cases, indicating that the GPAC-2 had a superior removal performance.

	Least squares mean (95 % CI)	
	Removal Effect ($RE_{m3/h}$) [m^3/h]	Removal Efficiency ($REff_{\%}$) [%]
GPAC-1	170 (154, 186)	27.8 (24.0, 31.6)
GPAC-2	236 (220, 252)	44.5 (40.7, 48.3)

these losses were the same under different scenarios and negligible with occupants present, regardless of whether the GPACs were operating or idled. Our approach did not follow exactly the protocol for testing the performance of a GPAC [40,43,45], where the loss rates are examined with an air cleaner both present and absent in a space. However, our approach was very similar to these protocols.

Only two GPAC brands that used similar air cleaning technologies were examined. It would be beneficial to conduct an equivalent, thorough investigation of other devices that utilize different air cleaning technologies. Our primary objective was to highlight the potential issues that should be considered when testing GPACs. The removal of organic compounds by GPACs can also vary because of differences in the structure of the activated carbon filters and the overall design of the GPACs [76,77]. Based on our results, we cannot generalize our results to all GPACs that use activated carbon filters. This underscores the need for standardised evaluation of the efficacy of GPACs.

We did not perform a detailed analysis of the *m/z* signals. The

Table 6
Organic compounds removed by GPAC as listed by ASHRAE 62.1 and those having low odour thresholds.

Number of Units	3	1	3	3	4	1	4	4
Total Airflow Rate [m^3/h]	306	306	918	1530	240	290	1160	2080
Mode	A	B	B	C	A	B	B	C
Brand	GPAC-1				GPAC-2			
Possible Organic Compounds	REff$_{\%}$ [%]							
Acetone	40.7	N/A	14.2	35.0	72.6	52.0	26.2	22.7
Acetic acid	47.0	N/A	31.9	10.2	93.7	82.8	35.7	20.8
Isoprene	44.4	11.3	15.1	13.0	59.6	46.7	25.8	14.9
Crotonaldehyde	47.0	16.3	16.2	12.7	71.7	46.2	25.8	15.9
2-Butanone (MEK)	25.1	13.0	11.4	14.6	71.3	48.9	27.9	15.0
Propanoic acid	44.6	53.8	24.4	9.9	77.8	62.2	29.6	16.6
Benzene	32.3	68.0	26.7	8.3	79.8	71.4	32.4	18.9
2-Pentanone	44.3	27.9	16.9	9.9	65.2	39.7	27.5	15.3
Butyric acid	65.5	25.0	21.2	17.6	99.2	88.3	27.6	14.2

compounds attributed to different *m/z* signals were not verified, nor were potential fragments from other compounds identified that might have contributed to the measured signals. The study did not intend to identify specific compounds but to evaluate the removal of a range of organic compounds from indoor air under different scenarios. It is advisable not to use our data to draw general conclusions regarding the capacity of the tested GPACs to remove specific compounds.

6. Conclusions

Based on the present measurements, the following key observations can be made:

(1) Of the forty-four *m/z* signals detected by PTR-ToF-MS, the data for twenty-two compounds demonstrated a robust fit to the mass balance equation allowing the reliable calculations of the decay rates. This indicates that not all identified organic compounds were effectively removed by the GPAC units.
(2) For the twenty-two *m/z* signals, representing different organic compounds and fragmentations, removal efficiencies varied widely, ranging from slightly above 8 % to 99 %.
(3) The calculated removal effects in m^3/h showed considerable variability across the compounds and the operation modes.
(4) Removal efficiency decreased with increasing airflow rate through GPACs.
(5) No single removal efficiency or removal effect could adequately characterize the performance of the GPACs examined across the range of compounds that were being removed.

The present study provides valuable insights that could be used when developing testing standards and guidelines for assessing the performance of air cleaners. We propose that current standards and testing protocols should be revised to ascertain appropriate evaluation of the performance of air cleaners, particularly in terms of their real-world performance.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT 4o in order to improve the readability and language of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

CRediT authorship contribution statement

Yiming Xiang: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Kanta Amada:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Asit Kumar Mishra:** Writing – review & editing, Validation, Software, Formal analysis. **Shinichi Tanabe:** Writing – review & editing, Supervision. **Lei Fang:** Writing – review & editing, Validation, Supervision. **Pawel Wargocki:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, 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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2025.116152.

Data availability

Data will be made available on request.

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