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The potential of mobile air cleaners for particle removal in school classrooms: A field study

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Abstract

In this field study, we assess the potential of using mobile air cleaners (MACs) to reduce the concentration of respiratory particles, responsible for the cross-infection of respiratory diseases, in school classrooms. We used three types of MAC which were found to yield comparably good performances in lab-controlled particle decay tests aimed at measuring their clean air delivery rates (CADR). The purpose of this field study is to evaluate the efficiency of these carefully pre-selected MACs in actual classrooms during typical teaching activities, hence determining whether such high-CADR devices are actually suitable in such real-life situations. The particle and CO_2 concentrations were measured continuously over 6 weeks in 15 classrooms of five primary schools in the Netherlands, three classrooms per school, each equipped with one of the three types of MACs which were turned ON either during the first or the last 3 weeks of the study and turned OFF otherwise. We found that the use of these MACs, with optimum number of devices, location and fan level settings, leads to a systematic reduction in the overall particle concentrations, typically by a factor 2.

Keywords

Air cleaning–dusts and PMs and microbes, Mobile air cleaners, Respiratory particle, Classroom, Disease transmission and control

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Introduction

Following the COVID-19 pandemic, indoor air quality (IAQ) has received more attention due to its probably critical role in the airborne transmission of respiratory infections via pathogen-laden respiratory particles (also called aerosols).[1–3] Respiratory particles, in general, are released during normal respiratory activities such as breathing, speaking, sneezing and coughing, and can remain suspended in the air for extended periods of time. Given that children spend a substantial portion of their time at schools, and that classrooms are typically characterized by high occupancy and prolonged exposure, these environments pose a particularly high risk for cross-infection among students and staff.[4,5] Accordingly, studies have highlighted the importance of proper ventilation and air cleaning for reducing respiratory particle concentrations in public indoor spaces.[6,7] In school classrooms, ventilation can often be improved through increased awareness and behavioral interventions, for example by using CO_2 monitoring to guide window opening.[8] However, the effectiveness of such measures depends strongly on occupant

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behavior, outdoor conditions and thermal comfort considerations, and may therefore be limited in practice, particularly during colder seasons. During the COVID-19 pandemic, school closures were implemented worldwide as a primary non-pharmaceutical intervention to limit outbreaks.[9] In retrospect, this approach had detrimental consequences for children's mental and physical health,[10,11] underscoring the need for robust mitigation strategies that remain effective under real-world classroom conditions when facing future challenges.

Importantly, the issues of inadequate ventilation and poor IAQ in school classrooms had already been documented prior to the COVID-19 pandemic. Studies conducted across various countries and regions have consistently reported that CO_2 concentrations in classrooms often exceed recommended limits, while ventilation rates frequently fall below the minimum required thresholds.[12–15] Besides, particulate matters (PMs) are identified as a significant source of indoor air pollution in classrooms.[16,17] High concentrations of PMs were also observed in many classrooms, which are linked to adverse health effects, including respiratory issues and increased absenteeism due to illness.[13,15–17] Nonetheless, in previous studies, PMs in classrooms were primarily attributed to outdoor sources such as traffic and industrial emissions,[15] while the emission from human respiratory activities was rarely considered. With the growing recognition of the risk associated with (infectious) respiratory particles, both indoor and outdoor sources of particulate pollution should be taken into account in strategies for improving IAQ in classrooms, to ensure occupants' health, comfort and wellbeing. However, this remains challenging under current infrastructural conditions, as the majority of schools rely exclusively on natural ventilation, while existing mechanical ventilation systems, where present, are often poorly designed, maintained, or intentionally limited to reduce expenses.[13,14,18] Furthermore, financial constraints play a role in restricting the feasibility of system upgrades or retrofitting efforts.[13,14,18,19]

Mobile air cleaners (MACs), as a more affordable and flexible solution, are therefore proposed for mitigating particle concentrations in classroom environments. Air cleaning is not a novel concept in the context of IAQ control, and previous studies have extensively demonstrated the benefit of using air cleaning devices to minimize particle concentrations in indoor spaces.[20–22] To date, MACs have been more frequently investigated in office or residential environments than in school classrooms. This is partly due to practical, regulatory and financial constraints, as schools are sensitive settings with limited flexibility for deploying and testing additional equipment during normal activities. Moreover, most commercially available devices were originally designed for office or residential use. Given the higher occupancy density, distinct ventilation practices, and prolonged exposure in classrooms, dedicated field studies in educational settings remain necessary. In recent years, researchers have begun to explore the feasibility of deploying MACs in classrooms, with most studies reporting promising particle removal performance, either through concentration decay experiments or in situ monitoring during regular lessons.[23–26] Despite these findings, previous research has generally lacked systematic comparisons among different MAC types, and device selection processes were often omitted. As a result, studies focusing on a single type of MAC offer limited guidance for practical implementation. To address this gap, our prior study aimed to develop a comprehensive strategy for using MACs in classrooms.[27] We first established a set of selection criteria, through which seven small to medium sized floor-standing MACs were selected, each representing diverse combinations of air cleaning technologies, airflow induction patterns, fan capacities, physical dimensions and other characteristics. These devices were then tested in a controlled mock-up classroom at the SenseLab, Delft University of Technology,[28] where their particle removal efficiency, noise and air velocity were evaluated using both objective measurements and subjective assessment. Consequently, the optimal configurations, comprising fan level settings, number of devices and location, were determined for each MAC type, and further validated in a university lecture room, where the comparison among the MACs was further completed, and strategies for practical use were proposed.[27]

Nonetheless, the applicability of these strategies under real-world classroom conditions remained uncertain. Therefore, the present field study aims to validate the proposed strategies by implementing several of the most promising MACs from the prior experimental study in actual school classrooms and assessing their effectiveness. By assessing their impact on particle concentration during typical school activities, this study seeks to provide evidence-based recommendations for the integration of air cleaning technologies in educational environments to enhance IAQ.

Methods

Schools and MACs

The field study was carried out over 6 weeks in 2023, from November 6th to December 15th, in five Dutch primary schools, labeled schools 1–5, covering age groups from 5 to 12 years old. The position of each school is shown on the map of Figure 1(a). The distance between the southernmost and the northernmost schools is 8.7 km. Schools were enrolled on a voluntary basis. All classrooms had a floor area ranging between 40 and 50 m^2 with a typical occupancy of 20–25 pupils. All classrooms have openable doors and windows for natural ventilation, school 1 also being equipped with a balanced mechanical ventilation system.

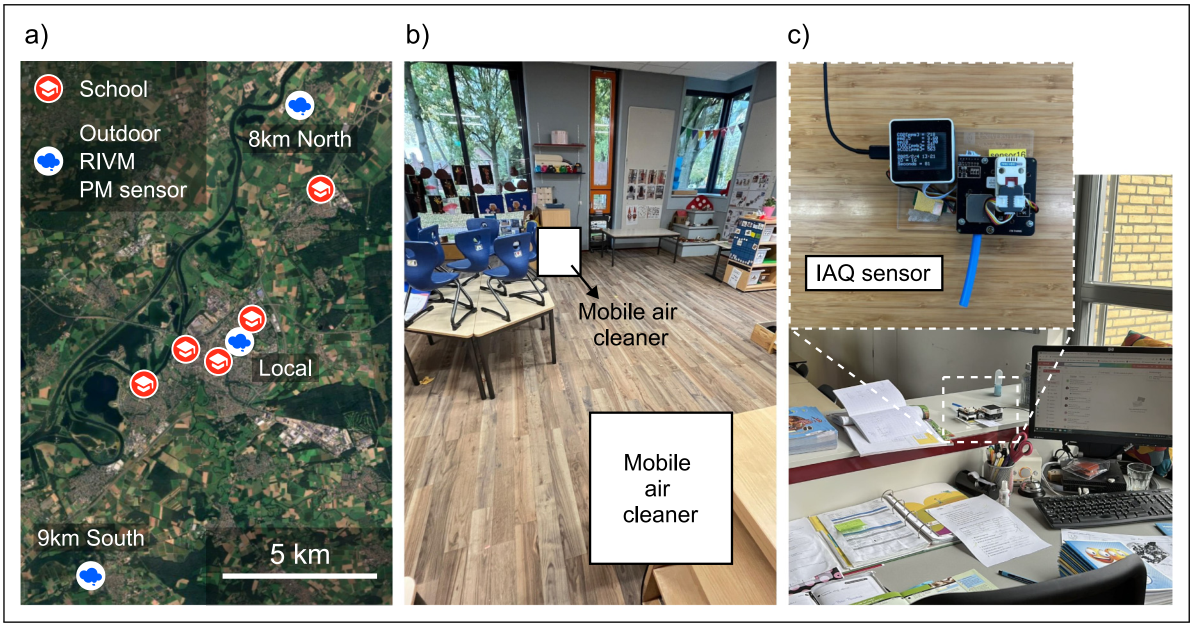


Figure 1. (a) Map of the geographical region of interest featuring the position of the five schools and of three public (RIVM) outdoor PM sensors. (b) Picture of a classroom showing the position of the two MACs (MAC-C), one at the front and one at the back. (c) Picture of an IAQ (Indoor Air Quality) sensor placed on a teacher's desk. The inset image offers a better visualization of the sensor.

Note that all classrooms used whiteboards, which excludes chalk as a potential source of (solid) particles (aerosols). This study was conducted as a pilot field investigation aimed at exploring the real-life performance of selected MACs in school classrooms; consequently, not all building-specific or operational parameters were documented in detail.

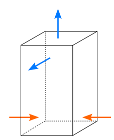
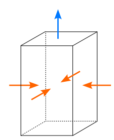
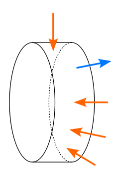
The three types of MACs used in this field study were selected based on their high clean air delivery rates (CADR) and acceptable air velocities and noise levels, as determined by lab-controlled particle decay tests and panel perception tests detailed in our previous (preliminary) study where seven small- to medium-sized floor-standing MACs were compared.[27] The three types of MACs used in this study are labeled MAC-A, MAC-B and MAC-C and correspond respectively to the devices labeled MAC4, MAC6 and MAC7 in our previous study,[27] see Table 1 for technical information. A summary of this previous study can be found in Ding & Bluyssen 2024.[29]

In each school, several classrooms were equipped with two of the same type of MACs (MAC-A, B, or C), one at the front and one at the back, with air supply facing the occupied area, see Figure 1(b). The power setting of each device, chosen based on our previous study,[27] was preselected so that teachers would only have to turn the device ON or OFF. We chose the maximum setting for MAC-A and MAC-B and a moderate setting for MAC-C since its maximum setting generates too much noise, see Table 1. The 6 weeks of the field study consisted of two periods of 3 weeks with MACs being either turned ON or OFF. MACs were turned ON for the first 3 weeks in schools 1, 4 and 5, where school directors and teachers were instructed to turn ON/OFF the devices at the beginning/end of each school day, and then kept OFF for the following 3 weeks. The opposite was chosen for schools 2 and 3 (MACs OFF for the first 3 weeks and ON for the 3 last).

Air quality measurements

The IAQ parameters investigated in this study were airborne particles and CO_2. Airborne particles, i.e., aerosols, can be either liquid droplets or solid particles coming from a variety of sources. Indoor sources include (i) respiratory droplets generated by humans when breathing, speaking, coughing, or sneezing, which are the ones responsible for respiratory disease transmission, (ii) dust (e.g., human dander and textile fibers) which can be aerosolized from surfaces via human activities (e.g., sweeping the floor or rubbing clothes) and (iii) mold. Outdoor sources include pollution particles generated by car traffic and nearby industrial sites carried by the wind, which may enter the room via natural (window opening) or mechanical ventilation.[30] The CO_2 concentration is often used as a proxy for the ventilation rate in spaces occupied by several persons.[30] Note that window status (open or closed) is not systematically recorded. Indeed, since each classroom is tested with MACs both ON and OFF, each classroom (ventilation and

Table 1. Characteristics of each mobile air cleaners (MAC). HEPA (filter), ES and AC stand for high- efficiency particulate air (filter), electrostatics and activated carbon, respectively. All three MACs are categorized H13 in terms of filtration efficiency. The number of devices and power settings are the ones chosen for our field study.

MAC type	Air cleaning technology	Airflow pattern	CADR ($PM_{2.5}$/PM_{10}) [m3/h] (selected setting)[a]	Noise level [dB(A)] (selected setting)[b]	Dimensions (cm)	Price (€) (including VAT)	Number of devices	Power setting (selected / total)
A	ES + AC		973/1140	45	34.0 × 34.0 × 85.5	1100	2	2/2
B	HEPA		1000/1195	45	33.2 × 33.6 × 60.6	500	2	8/8
C	HEPA		778/834	33	68.8 (Φ) × 25.4	1500	2	4/8

[a,b]CADR (clean air delivery rate) and noise level measured in prior laboratory tests[27] at the designated number of devices and power setting used in the present field study.

teacher habits regarding windows) is its own control, assuming no significant differences in such parameters between the ON and OFF periods. This is supported by the non-significant differences between the two periods in terms of CO_2 concentration which will be discussed in the 'Results and discussions' section.

In each school, three classrooms equipped with different MACs (namely one with MAC-A, one with MAC-B and one with MAC-C) were selected for air quality measurements. That is, 15 classrooms in total. We used $PM_{2.5}$ and PM_{10} sensors to measure the concentration of airborne particles, where $PM_{2.5}$ and PM_{10} levels correspond to the concentration of particles of size less than 2.5 and 10 μm in the air, respectively.

PM levels were measured by Nova SDS011 and Plantower PMS5003 sensors, two lowcost PM sensors widely used in, e.g., DIY air quality monitors. SDS011 sensors (range: 0–999.9 $\mu g/m^3$, accuracy: ±10%)[31] are considered to be more precise since $PM_{2.5}$ and PM_{10} concentrations are reported with one digit after the decimal point while PMS5003 sensors report integer PM values. PMS5003 sensors (range: 0–5000 $\mu g/m^3$, accuracy: ±10% in the range of $PM_{2.5}$ and PM_{10} concentrations <100 $\mu g/m^3$)[32] are considered to be more versatile since they also measure PM_1 levels (particles of size less than 1 μm). SDS011 sensors were used in schools 1, 2 and 4 and PMS5003 sensors were used in schools 3 and 5. We did not cross-calibrate sensors of different types, resulting in a potential systematic bias between SDS011 and PMS5003 readings. Our protocol is designed to circumvent this limitation since the effect of a MAC is quantified by comparing ON and OFF periods withing a given classroom, equipped with a given type of sensor. This ensures the reliability of the PM reduction factor between OFF and ON periods for each classroom.

The CO_2 concentration was measured by an MH-Z19B sensor (range: 0–2000 ppm, accuracy: ±50 ppm). The CO_2 and PM sensors were connected to a central unit (hereafter referred to as the 'IAQ sensor') from which data is saved on a SD card, with a logging interval of 5 min. A single IAQ sensor was placed in each of the 15 classrooms, usually on the teachers' desk, see Figure 1(c).

To gain some insight into the nature of the airborne particles present in classrooms, indoor PM levels were compared to values measured outdoor. Ideally, a sensor should have been placed outside of each of the five schools to measure the local outdoor air quality. This was unfortunately not done in this study. We therefore collected the $PM_{2.5}$ and PM_{10} values reported by the Dutch National Institute for Public Health and the Environment (RIVM) on the website www.samenmeten.nl (publicly available outdoor pollution levels across the country). We chose to extract the data from three outdoor PM (SDS011) sensors whose position is shown on the map of Figure 1(a). The reliability of the PM level readings of public (RIVM) outdoor sensors was confirmed by continuous measurements (not shown) of PM levels on the roof of the Science Park building of the University of Amsterdam for 6 weeks. These levels were found to be quantitatively similar to that of a public RIVM sensor situated 1 km away, with $PM_{2.5}$ values ranging between 1 and 40 $\mu g/m^3$.

Note that, while this paper focuses on air quality measurements, biological air sampling measurements were also performed in this field study, as well as absenteeism data analysis and interviews of teachers and pupils regarding the potential discomfort caused by the extra noise and air currents from the devices. These results, published separately,[33] provide a fuller picture on the beneficial and potentially negative effects of installing MACs in classrooms.

Data analysis

During the data cleaning process, it was found that although IAQ sensors worked properly most of the time during the 6-week period, some still showed no data for up to 2 days probably due to the teacher unplugging them by mistake and plugging them back on later. Furthermore, the IAQ sensor in the classroom of school 5 equipped with MAC-A stopped working soon after being installed and could not be fixed, and thus no result can be reported. In addition, teachers sometimes forgot to turn the MACs ON and these days are hence excluded from the data analysis. Wednesday December 6th is also excluded for all schools due to Sinterklaas break. In total, 30 days out of 30×14 days (30 days for 14 classrooms) were excluded for data analysis, i.e., 7% of the expected amount of data.

The data was further trimmed based on the schedule of each classroom, namely the unoccupied hours (breaks and outdoor activities) were excluded. Subsequently, all 5-min interval measurements within occupied classroom hours were aggregated to a daily summary value per classroom by calculating the median concentration. These daily summary values were then used as input for the statistical analyses. To assess overall differences between MAC ON and OFF periods and MAC types (A, B, C), linear mixed-effects models were fitted per IAQ parameter with MAC status and MAC type as fixed effects, while school, classroom (sensor) and day were included as random effects. For $PM_{2.5}$ and PM_{10}, standardized outdoor concentrations were included as an additional covariate to adjust for outdoor pollution levels. Interaction terms between MAC type and MAC status were tested but found non-significant, and were therefore excluded from the final models.

Additionally, several sensitivity analyses were performed. Residual diagnostics indicated mild heteroskedasticity for PM_{10} and more pronounced heteroskedasticity for $PM_{2.5}$; therefore, log-linear mixed-effects models were fitted to assess the robustness of the estimated MAC effects. In addition, daily maximum concentrations were used instead of daily medians within the same modeling framework. Finally, binomial mixed-effects models were fitted to assess the proportion of time during which indoor $PM_{2.5}$ concentrations exceeded 5 $\mu g/m^3$ (a threshold used by Banholzer et al.[34]) using the number of exceedances per classroom-day relative to the total number of valid observations as the outcome.

Results and discussions

Daily variations

Two typical time evolutions of the CO_2, $PM_{2.5}$ and PM_{10} concentration over 1 day (between 06:00 and 18:00) are presented in Figure 2 for the classroom of school 4 equipped with MAC-C (a) and for the classroom of school 2 also equipped with MAC-C (b) on different days within the first 3 weeks where MACs were respectively turned ON (a) and OFF (b) in these schools. Light data points correspond to unoccupied hours (breaks or outdoor activities).

The purpose of Figure 2 is not to compare PM values when MACs are ON (a) or OFF (b) since we consider two different classrooms, but rather to compare two different types of correlations between CO_2 and PM values. In Figure 2(a), after an initial rise in CO_2 at the beginning of the day, consistent with the arrival of pupils, the CO_2 concentration drops suddenly at around 10:00 while teaching activities are still taking place (no break), which indicates that windows must have been opened by the teacher. This is consistent with the fact that all classrooms were equipped with CO_2 meters prior to this field study and that teachers, aware of the danger of too high CO_2 levels, are used to open windows when they read high CO_2 values. This drop in CO_2 is accompanied by a significant rise in both $PM_{2.5}$ and PM_{10} concentrations above the background value which had barely increased upon the arrival of pupils in the classroom. This suggests that these additional particles are outdoor pollution particles entering the classroom via open windows. This negative correlation between CO_2 and PM values, observed throughout Figure 2(a) contrasts with the positive correlation observed in Figure 2(b) where an increase (resp. decrease) in CO_2 levels is systematically accompanied by an increase (resp. decrease) in PM levels suggesting that, in that case, most airborne particles measured indoor are generated by human activities. Both opposite scenarios are observed within our data across different days and classrooms, independently of MACs being

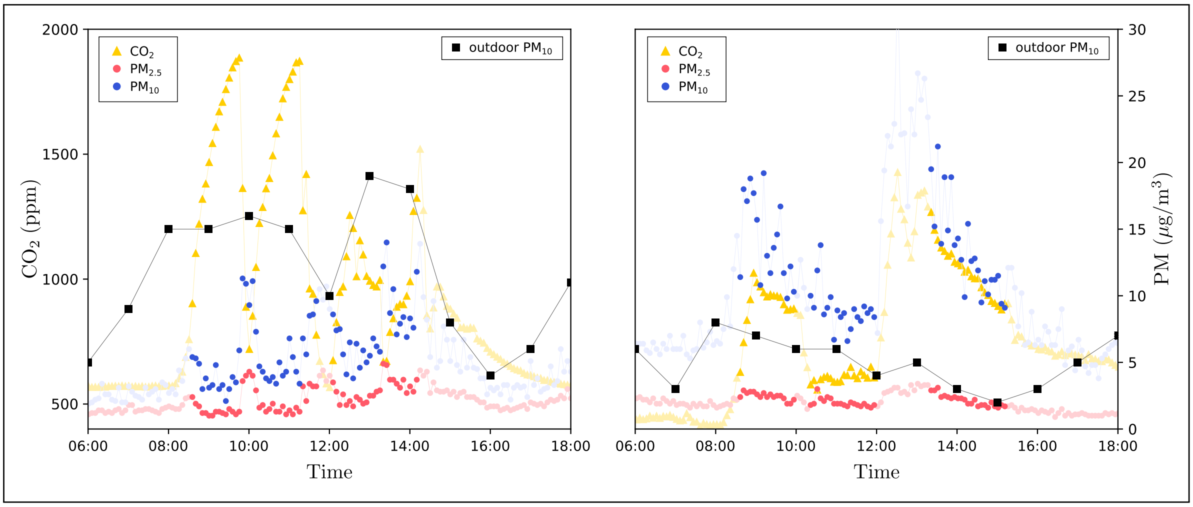


Figure 2. Typical time evolution of the concentration of CO_2 (left *y*-axis), $PM_{2.5}$ and PM_{10} (right y-axis, all axis common to both panels) between 06:00 and 18:00, in the classroom of school 4 equipped with MAC-C on Tuesday, 21 November 2023 (a) and in the classroom of school 2 equipped with MAC-C on Monday, 13 November 2023 (b). MACs were ON in (a) and OFF in (b) for these respective classrooms on these particular days. Light data points correspond to unoccupied hours (breaks or outdoor activities). The outdoor PM_{10} levels reported by the public (RIVM) sensor ('local', see Figure 1(b)) are also shown (right y-axis), one (averaged) data point per hour.

ON or OFF, hence preventing us from drawing general conclusions on the source (and therefore nature) of the particles present in the air. Figure 2 shows two of the most striking examples of positive and negative CO_2-PM correlations that we could find within all our data.

Link with outdoor pollution levels

The time evolution of PM concentrations, averaged over 1 day for each day within the 6 weeks of the field study (weekends and holidays excluded), are shown in Figure 3(a) ($PM_{2.5}$) and Figure 3(b) (PM_{10}). More precisely, for each classroom, each data point corresponds to the average over all times within occupied classroom hours (excluding breaks and outdoor activities) while, for outdoor PM levels reported by the three public (RIVM) sensors, each data point corresponds to the average over hours between 08:00 and 16:00. Each marker type corresponds to a specific classroom labeled by its school number and MAC type while the marker color indicates whether MACs were ON (green) or OFF (red) on each day (see legend). MACs were first ON for 3 weeks (first period) and then OFF for 3 weeks (second period) in schools 1, 4 and 5, and vice versa in schools 2 and 3. The general trend for indoor PM levels is illustrated by the darker green and red circular markers showing the average over all classrooms with MACs ON or OFF for each day. Note that, while both $PM_{2.5}$ and PM_{10} levels are shown for the 'local' public (RIVM) sensor (black square), only $PM_{2.5}$ levels are shown for the two other public sensors situated a few kilometers away (yellow and blue squares) (see Figure 1(b)). This is because, by the time we decided to add the data of these two other sensors, PM_{10} levels corresponding to this period were no longer available.

We observe in Figure 3(a) and (b) that outdoor pollution levels from the 'local' public sensor can vary significantly from day to day, with (daily average) $PM_{2.5}$ and PM_{10} concentrations ranging between 2 and 22 $\mu g/m^3$. In addition, indoor PM concentrations in all classrooms are found to be higher on days with higher outdoor pollution levels. This might be surprising since some schools are not close to the 'local' public sensor and one might hence expect strong differences in outdoor pollutions levels due to differences in, e.g., local road traffic intensity near the different schools. However, Figure 3(a) shows that the $PM_{2.5}$ levels reported by the public sensors 8 km north and 9 km south show similar trends as the local one, suggesting a fairly homogeneous distribution of pollution levels over the geographical region of interest. Indeed, days of relatively high pollution levels, such as the Fridays of weeks 2, 4 and 6 or the Wednesday of week 3, are clearly identifiable in Figure 3(a) and (b). This suggests that outdoor PM particles may be carried by the wind towards this geographical region while stemming from, e.g., industrial site activities.

This correlation between indoor and outdoor PM levels is strengthened in Figure 3(c) and (d) where the daily average indoor $PM_{2.5}$ (c) and PM_{10} (d) levels (in each classroom as well as averaged over all classrooms with MACs ON or OFF) are now plotted against the outdoor 'local' ones for each day. We observe an overall increase of indoor PM levels with outdoor ones. Note that the effect of MACs is already visible since green data points (MAC ON) are

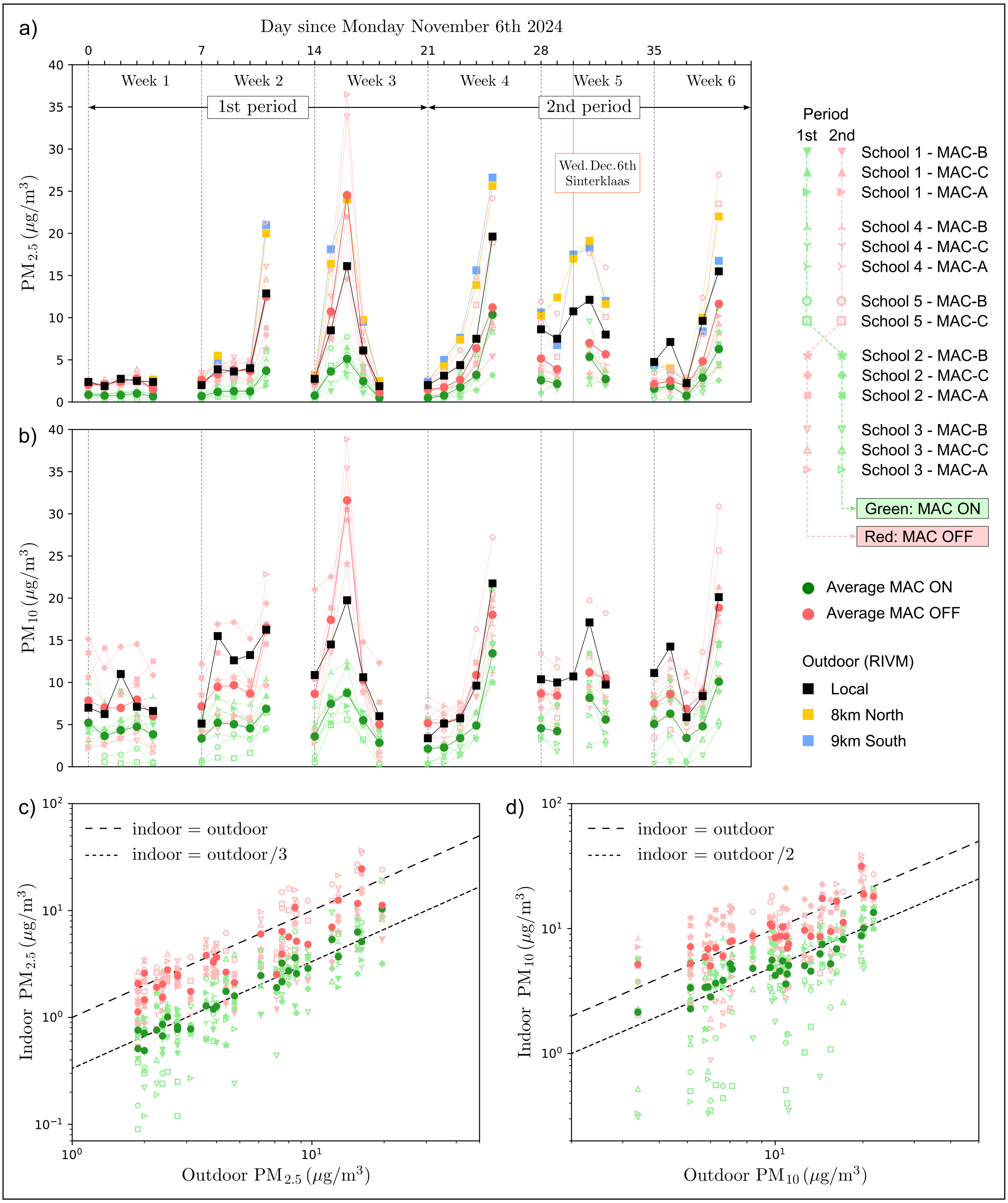


Figure 3. (a, b) Time evolution of the daily average concentration of $PM_{2.5}$ (a) and PM_{10} (b) in each classroom (one symbol per classroom, see legend) and of outdoor PM levels (squares) from the three public (RIVM) sensors (see Figure 1(a)). (c, d) Representation of the same data where the daily average indoor PM values (in each classroom) is plotted against the outdoor ('local') one. Green/Red corresponds to MACs being ON/OFF. The general trend for indoor PM levels is illustrated by the darker green and red circular markers showing the average over all classrooms with MACs ON/OFF for each day. There is no indoor data point on December 6th due to a Dutch holiday (Sinterklaas). The reference dashed lines in (c, d) are not fits.

generally below red ones (MAC OFF) in Figure 3. Modeling the relationship between indoor and outdoor PM levels, while adjusting for MAC ON/OFF status, showed that each 1 $\mu g/m^3$ increase in outdoor $PM_{2.5}$ and PM_{10} was associated with a significant average increase of 0.55 (95% CI: 0.47–0.63) and 0.61 (95% CI: 0.50–0.73) $\mu g/m^3$ in indoor concentrations, respectively.

This correlation between indoor and outdoor PM levels suggests that a significant fraction of the particles measured in classrooms in fact correspond to outdoor pollution particles entering via, e.g., open windows. Such correlation has indeed been reported by previous studies.[35,36] However, even if the fraction of respiratory particles (which are the ones of interest regarding virus transmission) was small compared to other types of particles, general conclusions on the efficiency of air cleaners can still be drawn since MACs are expected to filter particles of a certain size range with the same efficiency regardless of their source. In other words, if the total concentration of all types of particles (of a given size range) is found to decrease by a certain percentage (e.g., by 50%) when MACs are turned ON, we can reasonably expect that the concentration of respiratory particles (of the same size) will be reduced by that same percentage.

Comparing ON and OFF periods

To compare IAQ parameters between MAC ON and OFF periods, we first performed a descriptive comparison using daily summary distributions and subsequently conducted formal statistical analyses using mixed-effects models. Distributions of daily average concentrations (averaged over times within occupied classroom hours) of all three IAQ parameters ($PM_{2.5}$, PM_{10} and CO_2) are shown in Figure 4 for different classrooms using a violin plot representation. Each classroom, labeled by its school number and MAC type, features two violins labeled ‘1’ and ‘2’, corresponding to the first and second periods (15 working days each), respectively, with a color code indicating if MACs were ON (green) or OFF (red) during that period. We observe that the $PM_{2.5}$ (Figure 4(a)) and PM_{10} (Figure 4(b)) concentrations were systematically lower during the ON period compared to the OFF period for all classrooms, i.e., the ‘green violin’ is systematically below the ‘red’ corresponding one. By contrast, CO_2 average concentrations (Figure 4(c)) were either lower or higher during the ON period depending on the classroom.

To assess overall differences between MAC ON and OFF periods and MAC types (A, B, C), linear mixed-effects models were fitted and the results are shown in Table 2 and visually represented in Figure 5. The results confirm that PM concentrations were significantly lower during MAC ON periods compared to OFF periods, with average concentrations reduced by approximately 50% (both p-values <0.001). No significant difference was observed for CO_2 (p-value: 0.786). The observed reduction in PM was comparable across the three MAC types. All estimates were adjusted for outdoor pollution levels.

The fact that CO_2 concentrations are not systematically affected by MACs being ON or OFF suggests that roughly the same number of pupils were present during both periods, indicating that the systematic reduction in PM concentration cannot be caused by a systematic difference in the number of pupils between the two periods. Another possible bias is that a difference between the two periods was observed for outdoor $PM_{2.5}$ levels (but not for outdoor PM_{10} levels), as shown by the two last violins in Figure 4(a) and (b). As discussed in subsection ‘Link with outdoor pollution levels’, a significant fraction of the particles measured in classrooms corresponds to outdoor pollution particles entering via open windows. However, since the statistical model included the outdoor $PM_{2.5}$ and PM_{10} concentration levels, the found reduction is already adjusted for outdoor pollution levels and cannot be attributed to a systematic difference in outdoor pollution levels between the two. We note that most violins in Figure 4(a) and (b) have a thick bottom part and a slender upper part. This indicates that most days feature a low (daily average) PM concentration with few days featuring a significantly larger one. These ‘high PM concentration days’ are generally the same for all classrooms and correspond to high outdoor pollutions levels, as discussed in the subsection ‘Link with outdoor pollution levels’.

Sensitivity analyses

In addition to the statistical analysis presented in the ‘Comparing ON and OFF periods’ subsection, where we used linear mixed-effects models with daily median concentrations as input, three sensitivity analyses were performed.

Firstly, log-linear mixed-effects models (instead of linear) were fitted per IAQ parameter to assess overall differences between MAC ON and OFF periods and MAC types (A, B, C), with MAC status and MAC type included as fixed effects and school, classroom (sensor) and day included as random effects. For $PM_{2.5}$ and PM_{10}, standardized outdoor concentrations were included as an additional covariate to adjust for outdoor pollution levels. The log- linear models showed a reduction in indoor $PM_{2.5}$ and PM_{10} concentrations during MAC ON periods compared with MAC OFF periods ($PM_{2.5}$: −50.1%, 95% CI: −53.4% to −46.6%; PM_{10}: −47.9%, 95% CI: −52.0% to −43.5%), consistent with the results of the linear models.

Secondly, using the same log-linear mixed-effects framework, models based on daily maximum concentrations (instead of daily median) also showed lower indoor PM levels during MAC ON periods compared with MAC OFF periods ($PM_{2.5}$: −35.3%, 95% CI: −40.2% to −30.0%; PM_{10}: −33.7%, 95% CI: −39.6% to −27.3%).

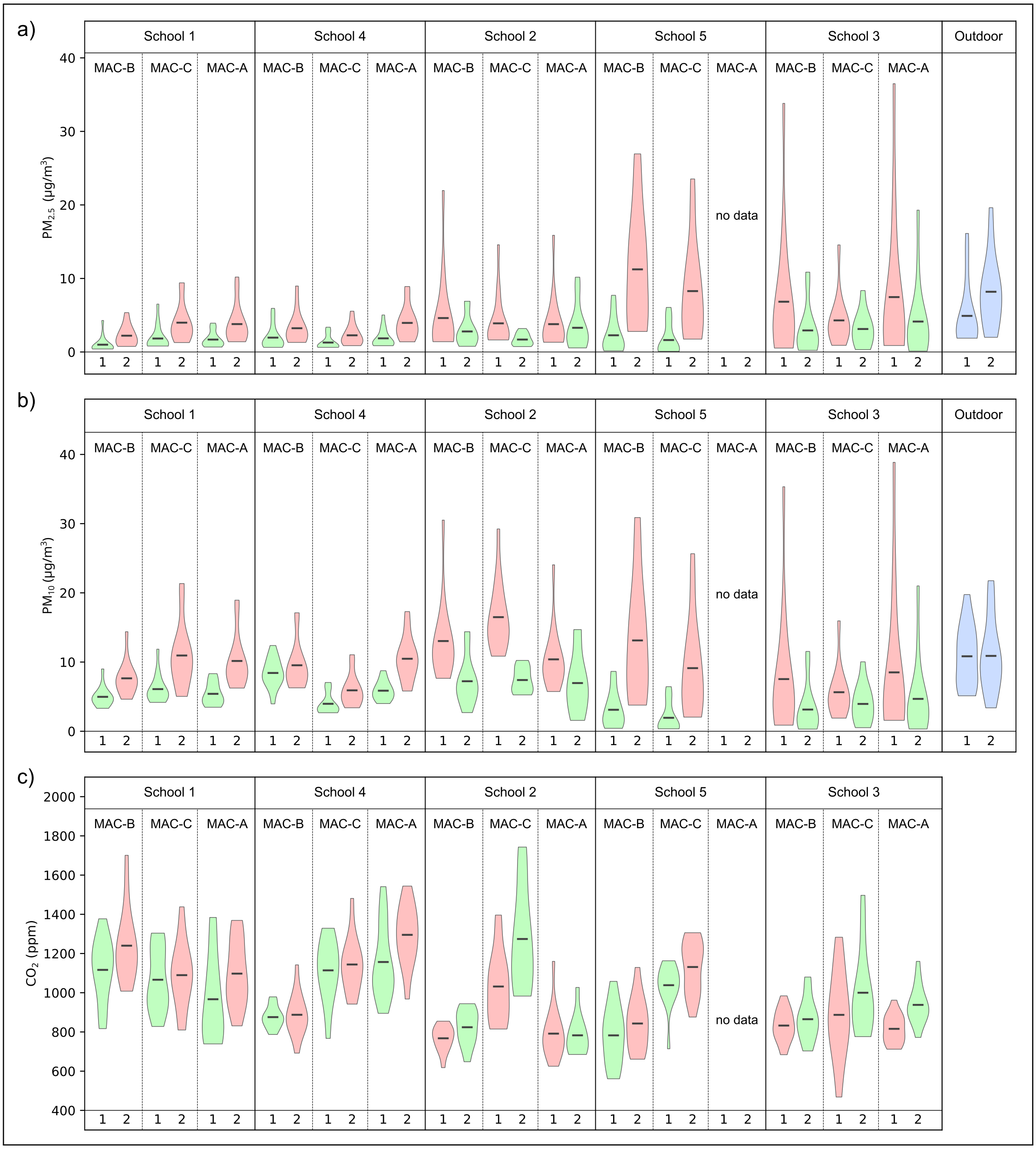


Figure 4. Violin plot representation of the distribution of daily average concentrations of $PM_{2.5}$ (a), PM_{10}, (b) and CO_2 (c) in each classroom, labeled by its school number and MAC type shown at the top of each panel, for the first ('1') and second ('2') 3-week period. The violin color indicates whether MACs were turned ON (green) or OFF (red) during that period. The mean value of each period is indicated by the grey horizontal segments in each violin. (a, b) The distribution of daily average concentrations of outdoor $PM_{2.5}$ and PM_{10} from the local RIVM sensor (Figure 1(a)) is also shown for both periods (blue violins).

Finally, binomial mixed-effects models were fitted to assess the proportion of time during which indoor PM concentrations exceeded recommended thresholds. For each classroom-day, the number of time points above 5 μg/m^3 for $PM_{2.5}$ (a threshold used by Banholzer et al.[34]) was modeled relative to the total number of valid observations, with

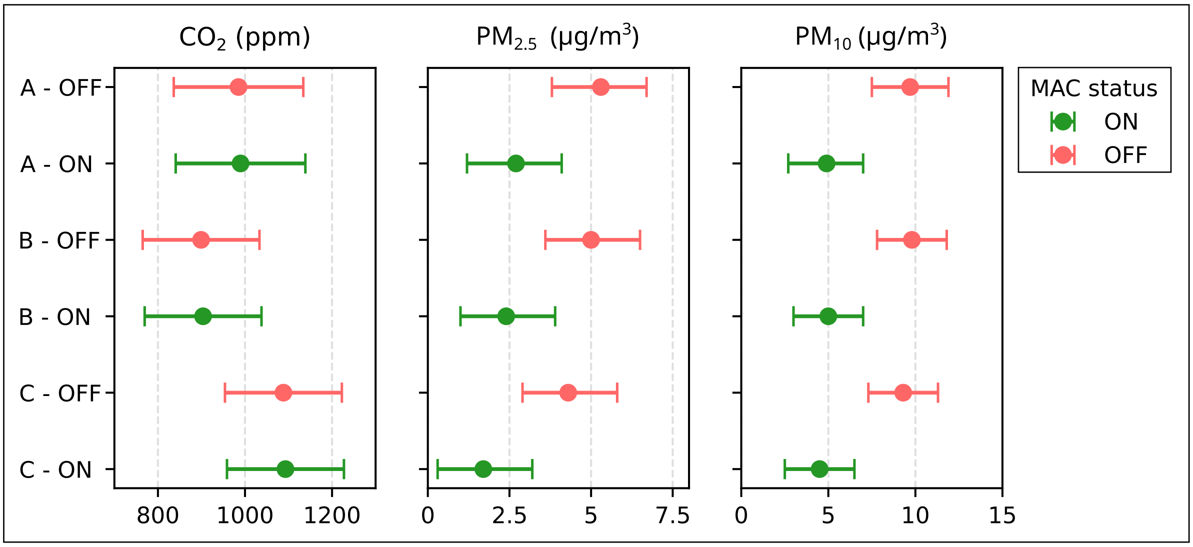


Figure 5. Visual representation of the overall effect of MAC status (ON/OFF) and type (A, B, C) on IAQ parameters. The results are shown per IAQ parameter CO_2 (left), $PM_{2.5}$ (middle), PM_{10} (right). Green/red corresponds to the MACs being ON/OFF. The effects are shown as the mean including the 95% confidence interval.

Table 2. Overall effect of MAC status and type on IAQ parameters. Means and 95% confidence intervals for each MAC type during the OFF and ON periods and associated change between the two periods, as well as *p*-values. The input numbers of the statistical analysis are daily summary values per classroom.

IAQ parameter	MAC type	OFF mean (95% CI)	ON mean (95% CI)	Change %	Change p-value
CO_2 (ppm)	A	985 (836–1134)	990 (841–1139)	+0.5	.786
	B	899 (765–1033)	904 (770–1038)	+0.5	
	C	1088 (954–1223)	1093 (959–1227)	+0.4	
$PM_{2.5}$ (μg/m^3)	A	5.3 (3.8–6.7)	2.7 (1.2–4.1)	−49.1	<.001
	B	5.0 (3.6–6.5)	2.4 (1.0–3.9)	−52.0	
	C	4.3 (2.9–5.8)	1.7 (0.3–3.2)	−60.5	
PM_{10} (μg/m^3)	A	9.7 (7.5–11.9)	4.9 (2.7–7.0)	−49.5	<.001
	B	9.8 (7.8–11.8)	5.0 (3.0–7.0)	−49.0	
	C	9.3 (7.3–11.3)	4.5 (2.5–6.5)	−51.6	

MAC status included as a fixed effect and school, classroom (sensor) and day included as random effects; standardized daily outdoor PM concentrations were included as additional covariates. MAC ON periods were associated with substantially lower odds of exceeding the $PM_{2.5}$ threshold compared with MAC OFF periods (OR: 0.036, 95% CI: 0.030 to 0.044).

Results for PM_1

Our statistical analysis was performed using concentrations of $PM_{2.5}$ and PM_{10} particles. However, respiratory particles (aerosol droplets) cover a wide size range, typically 0.1–10 μm with a peak around 1 μm.[37,38] Hence, PM_1 levels may be more representative of typical respiratory particles in terms of size. PM_1 data was only collected in classrooms of schools 3 and 5 equipped with PMS5003 sensors, classrooms of schools 1, 2 and 4 being equipped with SDS011 sensors which are more precise but which only measure $PM_{2.5}$ and PM_{10} levels. The results for PM_1 are comparable to the results of $PM_{2.5}$ for these classrooms in terms of daily average concentrations. Namely, we observe a systematic reduction of PM_1 levels when MACs are ON, with reduction factors similar to the ones in Figure 4(a) for $PM_{2.5}$. This suggests that MACs are effective not only on $PM_{2.5}$ and PM_{10} particles but also on smaller particles representative of respiratory aerosol sizes. Furthermore, the time evolutions of PM_1 concentrations are comparable to that of $PM_{2.5}$ and PM_{10} identified in Figure 3(a) and (b), i.e., days of high $PM_{2.5}$ and PM_{10} levels also feature high PM_1 levels. This suggests a non-negligible influence of outdoor pollution on indoor PM_1 levels.

The methods used to analyze $PM_{2.5}$ and PM_{10} data could not be used to analyze PM_1 data. Indeed, these methods include outdoor PM levels as a covariate while the public RIVM sensor used to collect outdoor PMs is a SDS011 sensor which only measures $PM_{2.5}$ and PM_{10} levels. However, since the reduction of PM_1 levels is observed in both schools 5 and 3, one with MACs ON during the first 3-week period and the other with MACs ON during the second 3-week period, it is unlikely that this reduction is caused by a systematic difference in outdoor PM_1 levels between the two periods.

Limitations

For future research, first, while this field study demonstrated the effectiveness of MACs in reducing primarily $PM_{2.5}$ and PM_{10} concentrations, it is suggested to collect more data for PM_1 particles, both indoor and outdoor, to confirm their reduction due to MACs. Moreover, placing multiple sensors in different locations would help map particle distribution, as done with CO_2 in a previous study,[39] and optimize device placement. Expanding research across a broader range of schools would also be beneficial to ensure adequate statistical power and valid comparisons.

Second, as this study relied on a regional public sensor to estimate outdoor pollution levels, it is recommended to also incorporate school-specific outdoor measurements for more precise indoor-outdoor comparisons. In particular, our data (not shown) suggests that when a pollution cloud hits the geographical region of interest, it hits different schools at different times, with a typical delay of a few hours relative to the location of the outdoor PM sensor for schools situated far from it. This is why we used daily summary values (withing teaching schedule) for PM levels in our data analysis. Measuring outdoor PMs at school level would hence enable a finer time resolution.

Third, future studies should consider using a more precise PM measurement method to (cross-) calibrate the readings of low-cost PM sensors to avoid any data heterogeneity. Indeed, in this study, we used both SDS011 (same as the public outdoor sensor) and PMS5003 PM sensors depending on the school to ensure that the PM reduction effect is not sensor-type dependent. However, these sensors were not cross-calibrated, resulting in a potential bias in PM readings across different sensor types, leading to data heterogeneity which might affect the school-level random effects in our mixed-effects models. We re-iterate that this limitation of our protocol does not invalidate our results since the MAC ON and OFF periods are compared for the same type of sensor in each classroom (one sensor per classroom), hence ensuring that the PM reduction ratio is calculated for a fixed sensor type.

Finally, our study shows similar CO_2 levels across MAC ON and OFF periods for each classroom, suggesting constant teacher window-opening habits. However, future studies should consider window status (open/closed) monitoring in order to explore the potential confounding effect of teachers opening windows systematically more often during either MAC ON or OFF periods. Other improvement routes include identifying and monitoring time-related confounders other than outdoor PM levels such as temperature, wind speed/direction, humidity, seasonal ventilation behavior changes, as well as the daily classroom-level occupancy to adjust for temporal variation in the number of pupils. Indeed, since ON and OFF periods were time-separated, unmeasured temporal trends could partially bias the results.

Conclusions and recommendations

This field study aimed at quantifying the performance of the three best commercially available MACs identified in our previous study in real-world classroom environments. These MACs were measured to have high CADR in lab-controlled aerosol decay test.[27] Our study confirms that these three MACs can indeed also significantly reduce the concentration of airborne particles (i.e., aerosols) in classrooms during normal teaching activities, typically by a factor 2. Across 15 classrooms in five Dutch primary schools, the operation of MACs led to a systematic reduction in both $PM_{2.5}$ and PM_{10} concentrations, typically by a factor of two, regardless of MAC type, classroom characteristics, or PM sources. Although variation in performance was noted between classrooms, no single MAC consistently outperformed the others across all settings. This suggests that several options can be equally viable for practical implementation, provided they meet certain baseline criteria for clean air delivery and user acceptability. Furthermore, the study found a correlation between indoor and outdoor particulate levels, supporting the interpretation that a considerate portion of particles present indoors originate from outdoor sources. This reinforces the dual value of MACs in both mitigating respiratory particles and improving general IAQ by filtering outdoor pollutants. Overall, our findings support the integration of MACs into school IAQ strategies as a flexible and evidence-based intervention.

From a practical standpoint, the results support the use of MACs as an effective and immediately applicable measure for improving IAQ in classrooms, especially where mechanical ventilation is limited or absent. All three tested devices achieved comparable reductions in particulate matter, suggesting that multiple commercially available options can be effective when configured appropriately. In this study, MACs were operated at fixed power settings with simple on/off controls, requiring minimal effort from teachers, while real-life use may also benefit from more flexible operation, such as making adjustments to the devices according to the preference under different activities, or the need for controlling infection risk.

Authors' contributions

All authors contributed equally to the preparation of this manuscript.

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