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Technical performance and perceived feasibility of mobile air cleaning devices in classrooms: A pilot study

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ABSTRACT

During respiratory virus outbreaks, mobile air cleaning devices (MACs) are increasingly considered in schools as a preventive measure. However, evidence on their real-world performance, feasibility, and potential health impact in classroom settings remains limited. This pilot study was conducted to inform the design of a future large-scale trial by providing a comprehensive evaluation of MACs in primary school classrooms, integrating technical performance (including indoor air quality and airborne microbial assessments), user-perceived feasibility, and the suitability of illness-related absenteeism as a potential pragmatic outcome measure for infection rates. A randomized cross-over study was conducted in five Dutch primary schools, involving 45 classrooms equipped with MACs. Each classroom alternated between three-week periods with the devices switched on and off. Indoor air quality was assessed in a subset of classrooms using sensors for CO₂ and particulate matter, while airborne microbial contamination was monitored through air dust sampling and molecular testing. Illness-related absenteeism was evaluated as a potential outcome measure. MACs effectively halved indoor particulate matter levels, confirming their technical performance. This reduction did not translate into a measurable reduction in airborne microbial contamination, although such contamination was successfully detected. Feasibility assessment revealed low acceptability among teachers due to reduced environmental comfort. Absenteeism was identified as a suitable proxy for infectious diseases, with simulations indicating that a future cluster-randomized trial would require 40–70 schools to detect a 20–25% reduction in absenteeism.

Introduction

Indoor air quality (IAQ) in schools is recognized as an important factor for children's health, cognitive performance, and overall well-being [1]. The COVID-19 pandemic intensified attention to IAQ by highlighting the role of airborne transmission in the spread of respiratory pathogens [2]. Schools, where children spend many hours in shared indoor spaces with close contact, were considered key settings for transmission [3]. This concern was reflected in the widespread school

closures, implemented globally to protect public health [4]. Mitigating school-related transmission of infectious diseases during epidemics and pandemics is therefore essential to safeguard student health, maintain educational continuity, and limit broader community spread.

Prior to the COVID-19 pandemic, IAQ standards in classrooms primarily aimed to balance thermal comfort and energy efficiency, typically recommending ventilation rates of 4–5 L/s per person based on outdoor air supply [5]. However, a national assessment conducted in 2020 revealed that only two-fifths of Dutch primary and secondary

Abbreviations: ARI, acute respiratory infection; CFIR, Consolidated Framework for Implementation Research; CI, confidence interval; CO₂, carbon dioxide; EDCs, electrostatic dustfall collectors; ECAI, equivalent clean airflow; GI, gastrointestinal illness; GLMM, generalized linear mixed-effects model; IAQ, indoor air quality; IQR, interquartile range; MAC, mobile air cleaning device; PBS, phosphate buffered saline; PM_{2.5}, particulate matter < 2.5 μm; PM₁₀, particulate matter < 10 μm; QPCR, quantitative polymerase chain reaction; RSV, respiratory syncytial virus; SD, standard deviation.

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schools met these pre-pandemic standards [6]. The pandemic prompted a shift in focus from comfort-based criteria toward infection control. New guidelines, such as ASHRAE Standard 241–2023, introduced the concept of equivalent clean airflow (ECAi), which integrates the combined effects of outdoor ventilation, air filtration, and active air cleaning on the removal of infectious aerosols [7]. The recommended minimum ECAi of 20 L/s per person under infection risk management mode represents a substantial increase over previous norms and exceeds the design capacity of most existing school ventilation systems.

To help bridge this gap, air-cleaning strategies have been proposed as a complementary approach to ventilation for improving IAQ [8]. Air-cleaning devices may enhance IAQ by removing virus-laden particles from recirculated air. Among them, mobile air cleaning devices (MACs) are of particular interest due to their portability, relative affordability, and ease of deployment. Although originally developed for residential or office environments, recent studies have demonstrated that MACs can reduce aerosol concentrations in school classrooms by up to 90%, depending on device characteristics such as clean air delivery rate (CADR), positioning within the room, and background ventilation conditions [9–18]. In addition to aerosol removal, several studies have reported practical considerations related to device deployment, including noise generation, airflow perception, and spatial constraints within classrooms [19,20]. A smaller body of work has explored health-related outcomes associated with MAC use, including estimated inhaled dose as an exposure metric, as well as respiratory symptoms and illness-related absenteeism [9,20]. These different dimensions of MAC use in classrooms have typically been investigated separately, with most studies focusing on technical performance rather than evaluating technical performance, perceived feasibility, and health-related outcomes within a single real-world study design. As a result, their implementation in school settings warrants further real-world evaluation.

We therefore conducted a randomized cross-over pilot study in five primary schools to inform the design of a future large-scale trial evaluating the impact of MACs on respiratory infection rates in school settings. The pilot combined assessment of technical performance (through monitoring of generic IAQ parameters and airborne microbial contamination), perceived feasibility during routine classroom use (through surveys and interviews with teachers and students), and the suitability of illness-related absenteeism as a pragmatic proxy outcome measure for respiratory infection rates (through surveys on reasons for absenteeism and sample-size simulations). Together, these elements provide a comprehensive basis for designing the future trial, the results of which will support evidence-based decisions on the use of MACs as part of broader strategies to mitigate the impact of respiratory infections on education and public health.

Methods

Study design and school selection

A randomized cross-over pilot study was conducted between November and December 2023 to assess the performance and feasibility of MACs in Dutch primary school classrooms. Five schools (designated School 1 to School 5) belonging to the same regional school community voluntarily participated after being selected from a pool that had previously expressed interest in MAC-related research. Jointly, the five primary schools had a student population of 1654. Schools were eligible if they agreed to operate the MACs during school hours according to the study protocol, could provide aggregated absenteeism data per student group, were willing to distribute anonymous online health questionnaires to absent students, facilitated weekly study visits, and enabled in-class anonymous surveys among teachers and students. Schools were invited to an online information session and formally included in the study upon providing consent. A total of 45 classrooms were included in the study, 8–10 per school. The selected classrooms covered all age groups (5–12 years old) and were similar in physical layout, with floor

areas ranging from 40 to 50 m² and typical occupancy between 20 and 25 individuals. All classrooms had multiple openable windows and doors for natural ventilation; those in School 1 were additionally equipped with a balanced mechanical ventilation system.

Selection and placement of MACs

Three mobile air cleaning devices (referred to as MAC-A, MAC-B, MAC-C) were selected based on previous experimental studies (MAC4, MAC6, and MAC7, as described by Ding et al. [8]). Selection of MAC models was based on aerosol removal efficiency using Clean Air Delivery Rate (CADR), and user comfort including measured and perceived noise level and air velocity. In the laboratory tests [8], different configurations (including fan setting, placement, and number of devices) were evaluated for each type of MAC, and the optimal conditions were determined accordingly. Detailed information on the selected MACs is summarized in Table 1. For the three MACs selected in the present study, it is recommended to employ two devices per classroom, with a diagonal placement (one at the front and one at the back), directing airflow toward the occupied area [8]. However, adjustments were often required due to limited space and classroom layout. In addition, many classrooms lacked sufficient power outlets, necessitating the use of extension cords and splitters.

Although three different MAC types were used, their individual performance is not the focus of this paper; detailed comparisons are reported elsewhere [21]. Instead, all devices were evaluated collectively to assess overall performance and feasibility. Each classroom followed a cross-over schedule consisting of a three-week period with the MACs operating (ON period) and a three-week period without MAC operation (OFF period), this planning is schematically depicted in Fig. 1. The order of these periods was randomized across schools: Schools 1, 4, and 5 began with the ON period, while Schools 2 and 3 started with the OFF period. The MACs were delivered and installed during the first week of November 2023. Teachers and school staff were instructed to switch on the MACs at the start of each school day and turn them off at the end, ensuring that the devices operated only during school hours. During weekly school visits, the setting and placement of the MACs were checked by the study team to ensure correct implementation.

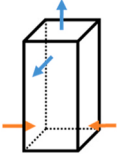
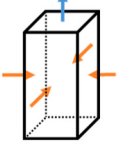
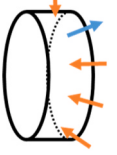
Monitoring technical performance of MACs – Generic IAQ parameters

The efficiency of MACs at removing aerosols from the air in classrooms was evaluated by comparing IAQ measurements between the ON and OFF periods. Detailed methods are reported elsewhere [21]. In short, IAQ was monitored in three classrooms per school (15 in total), using sensors typically placed on the teacher's desk. Data was saved on an SD card with a logging interval of 5 min. The monitored parameters were:

- CO₂ (carbon dioxide) concentration [ppm] used as a proxy for human occupancy.
- PM_{2.5} (particulate matter with an aerodynamic diameter <2.5 μm) concentration [μg/m³].
- PM₁₀ (particulate matter with an aerodynamic diameter <10 μm) concentration [μg/m³].

Data cleaning excluded unoccupied classroom hours based on weekly schedules, as well as days when MACs were not operated or when schools were closed. This resulted in the exclusion of 30 out of a possible 420 classroom days (7% of the total expected dataset). As a preprocessing step, the 5-minute interval measurements during school hours were aggregated to daily summary values per classroom: the median concentration, representing the daily average level, and the 97.5th percentile concentration, representing the daily peak level. These summary values were then used as input for the statistical analyses. To assess overall differences between MAC ON and OFF periods, linear

Table 1
Characteristics of the selected mobile air cleaners.

Device	Air cleaning technology ^a	Airflow pattern	CADR (PM _{2.5} / PM ₁₀) [m ³ /h] ^b	Noise level [dB(A)] (selected setting) ^c	Dimensions [cm]	Price [€] (including VAT)	Number of devices	Power setting (selected / total)
MAC-A	Electrostatic		973 / 1140	45	34.0 × 34.0 × 85.5	1100	2	2 / 2
MAC-B	HEPA		1000 / 1195	45	33.2 × 33.6 × 60.6	500	2	8 / 8
MAC-C	HEPA		778 / 834	33	68.8 (Φ) x 25.4	1500	2	4 / 8

^a All MACs were equipped with H13 HEPA filters.

^b CADR measured in prior laboratory tests [8] at the designated number of devices and power setting used in the present field study.

^c Noise level measured in prior laboratory tests [8] at the designated number of devices and power setting used in the present field study.

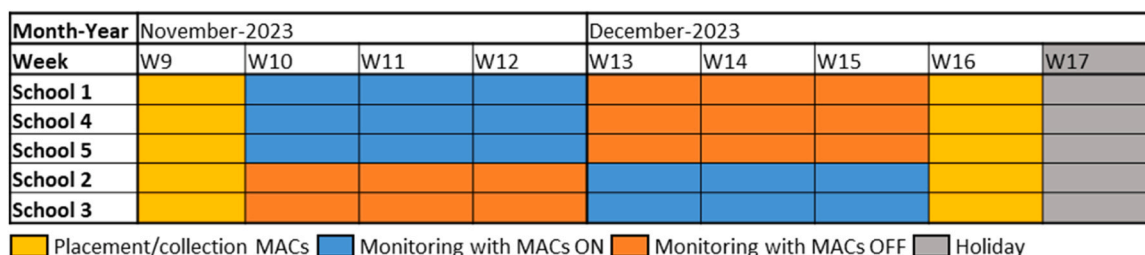


Fig. 1. Schematic overview of the cross-over study design. Each classroom followed a six-week schedule comprising two conditions: a three-week period with MACs in operation (ON period; in blue) and a three-week period without MAC operation (OFF period; in orange).

mixed-effects models were fitted with a random intercept for school, classroom (sensor), MAC and day, while MAC status (ON/OFF) was included as a fixed effect. These models were fitted in R version 4.1.3 using the lmerTest package version 3.1.3.

Monitoring technical performance of MACs – Airborne microbial contamination

Airborne microbial contamination was assessed in all 45 classrooms participating in the MAC intervention. To evaluate the impact of the MACs, samples collected during ON and OFF periods were compared. In addition, 14 comparable classrooms without MACs, located in three of the schools, were sampled to provide reference data on temporal changes unrelated to the intervention. Non-intrusive air sampling was conducted using Electrostatic Dustfall Collectors (EDCs) [22]. EDCs were placed in low-sided cardboard boxes suspended from the center of classroom ceilings (> 30 cm below the ceiling and ≥2 m above the floor). Placement deviated slightly in a few classrooms due to practical constraints. Samplers were collected after three weeks of air exposure and replaced with new ones for a second three-week period. After collection, samples were stored at -80 °C until DNA and RNA extraction. Prior to extraction, samples were thawed, mixed with 10 ml of 1:1 LGC lysis buffer and Dulbecco’s Phosphate Buffered Saline (PBS), agitated on a roller for 30 min, and placed on ice. This was followed by

total nucleic acid extraction for bacterial targets using the LGC DNA kit, as described by Fakunle et al. [23], and RNA extraction for viral targets using the Zymo RNEasy kit according to the supplier’s instructions.

Bacterial markers representing healthy human microbiome niches (*Staphylococcus aureus*, *S. salivarius*, *S. epidermidis*, and *Moraxella catarrhalis*), 16S rRNA as a marker of total bacterial load, and three viral targets associated with common seasonal infections (respiratory syncytial virus (RSV), influenza A and B) were analyzed by qPCR and reverse transcript qPCR, respectively. All samples were analyzed in duplicate on a BioRad CFX 384 with negative controls included, using 50 PCR cycles. Quantification was based on standard curves generated from synthesized gBlock fragments. Field blanks (sealed during sampling) and laboratory blanks were included to monitor background contamination. qPCR Ct values were inverted (50 – Ct), so that higher values correspond to higher microbial abundance. Microbial outcomes from classrooms during MAC ON and OFF periods were compared using paired *t*-tests, or Wilcoxon signed-rank tests when normality assumptions were not met. Reference classrooms without MACs were analyzed likewise, by comparing the two three-week study periods. Statistical analysis was performed in RStudio (version 4.4.0).

Assessment of perceived feasibility of MAC implementation

To assess the perceived feasibility of MAC implementation in

primary schools among administrators, teachers and students, we conducted a mixed-method study combining qualitative in-depth interviews with surveys, applying the Bowen and CFIR frameworks [24,25]. The survey was web-based and anonymous, included 5-point Likert scale response options, and was completed by students ($n = 274$) during the control period and by 213 and 136 students at two time points during the intervention period. Teachers completed the survey with 13 respondents in the control period and 12 at both intervention time points. Responses were summarized as percentages of positive, neutral, and negative answers for each item. Interviews with teachers ($n = 10$), school administration ($n = 3$), and students ($n = 18$) were conducted to explore experiences in more depth. Staff interviews were held online via Teams and lasted 30–45 min, while student interviews were conducted face to face in schools and lasted 6–15 min. Open-ended questions encouraged participants to elaborate on their own perspectives. The full methods and evaluation are reported elsewhere [26]. Here, we focus on the main findings from the domains of acceptability, demand, and implementation.

- Acceptability: teachers' expectations of MACs and the satisfaction of administrators, teachers and students.
- Demand: teachers' likelihood of future use and willingness to recommend MACs.
- Implementation: perceived ease of placement and use.

Evaluation of MAC efficacy based on illness-related absenteeism

To assess the potential of illness-related school absenteeism as an outcome measure for MAC effectiveness, data were obtained from the administrative systems of the five participating schools. The dataset covered the first half of the 2023/24 school year, from the summer to the Christmas holidays, including the MAC study period in November and December. Absences were recorded per classroom as episodes, each with a start and end date and a recorded reason for absence (non-authorized, authorized, or illness). Only illness-related absences were included in the analysis. Weekly illness-related absenteeism rates were calculated as the total number of illness-related absent days divided by the total number of student school days for each week. Absenteeism prevalence was expressed as the cumulative average number of illness-related absent days per student across the half-year period. The average weekly absenteeism rate and prevalence were estimated using a multilevel generalized linear mixed-effects model (GLMM) with a negative binomial distribution and random effects for school and class. An additional variable indicating MAC status (1 for MAC on, 0 for MAC off) was included to evaluate the effect of the MACs during the MAC study period. For the GLMM, the R package *glmmTMB* (version 1.1.9) was used.

Estimation of disease burden targetable by MACs

To gain further insight into the causes of illness-related absences, an anonymous online survey was conducted among parents of absent students during the MAC study period. Respondents reported the main reason for absence and one or more symptoms from a predefined list. Reported cases were classified as acute respiratory infection (ARI), gastrointestinal illness (GI), or other/unknown using a rule-based approach that combined the reported reason and symptom profile, as previously described [27]. In short, ARI classification was primarily based on the presence of respiratory symptoms such as coughing or runny nose, particularly when combined with cold/flu as the reported reason. Parents were also asked whether similar symptoms had occurred among household members. Based on their responses, each episode was classified as either 'prior household symptoms' (if symptoms had started earlier in the household) or 'no prior household symptoms' (suggesting the child was the index case who likely contracted the illness outside the household, possibly at school). To estimate the number of illness-related

absent days attributable to school-related ARI over the first half of the 2023/24 school year, we combined the overall absenteeism prevalence from that period with the proportion of absences classified as ARI and the proportion without prior household symptoms, both derived from the illness survey conducted during the MAC study period. The mean and standard error of these three parameters were used to generate 100,000 bootstrap samples, with each iteration calculating their product.

Sample size calculation for follow-up trial

To inform the design of a future cluster-randomized trial, we conducted simulation-based power analyses to estimate the number of schools required to detect a meaningful reduction in illness-related absenteeism. The full methodology is described in a separate manuscript [28]. In short, illness-related class-level absenteeism rates from the five schools participating in the pilot study from the school year 2022/23 were used as input. A negative binomial regression model was applied to this absenteeism data to model illness-related absenteeism at the class level per school period, with the school year divided into ten school periods of around four weeks. Based on this model, we simulated class-level absenteeism datasets for 50,000 hypothetical schools. Trial scenarios were then defined by varying parameters, including the expected effect size and study duration. For each scenario, we estimated the number of schools required to detect the expected intervention effect with 80% power. We report results from four scenarios, combining:

- Effect size: a 20% or 25% reduction in illness-related absenteeism due to an intervention
- Study duration: a full school year or a shorter period from the autumn break to the May break

Results

Impact of MACs on generic IAQ parameters

To evaluate the impact of MACs on IAQ, we compared daily average concentrations of three IAQ parameters between the MAC ON and OFF periods across 15 classrooms. Fig. 2A illustrates the time evolution of these parameters on two representative school days, depicting typical classroom conditions with MACs turned OFF and ON. Lighter data points indicate unoccupied periods, such as breaks or outdoor activities. CO₂ concentrations showed an initial rise at the start of the school day, consistent with pupil arrival, and dropped during breaks. Across the full dataset, CO₂ concentrations remained comparable between MAC ON and OFF periods. The presence of MACs led to a statistically significant reduction of particle (PM_{2.5} and PM₁₀) concentrations for all classrooms, regardless of the type of MAC being used or whether the intervention occurred during the first or second 3-weeks period. Results from the fitted linear mixed models (Fig. 2B) showed that, during MAC ON periods, daily average PM_{2.5} and PM₁₀ concentrations were reduced by 53.1% and 50.0%, respectively, and daily peak concentrations were reduced by 41.9% and 40.0%, respectively.

Impact of MACs on microbial contamination

EDC samplers proved suitable for assessing airborne microbial load in school classrooms. In nearly all EDC samples (99.1%) 16S rRNA, used as a marker of total bacterial load, was detected at quantifiable levels. Detection of specific common bacterial species was less frequent, with the following proportions of samples positive (signal above detectable limit) and quantifiable (signal within the standard curve): *S. salivarius* (66.5%; 43.0%), *S. epidermidis* (67%; 63.5%), *S. aureus* (59.1%; 56.5%), and *M. catarrhalis* (61.7%; 58.7%). None of the samples were positive for Influenza A or Influenza B viral RNA, while 25.2% of the samples tested positive for RSV RNA (21.3% quantifiable).

To assess the impact of MACs on airborne microbial load, paired

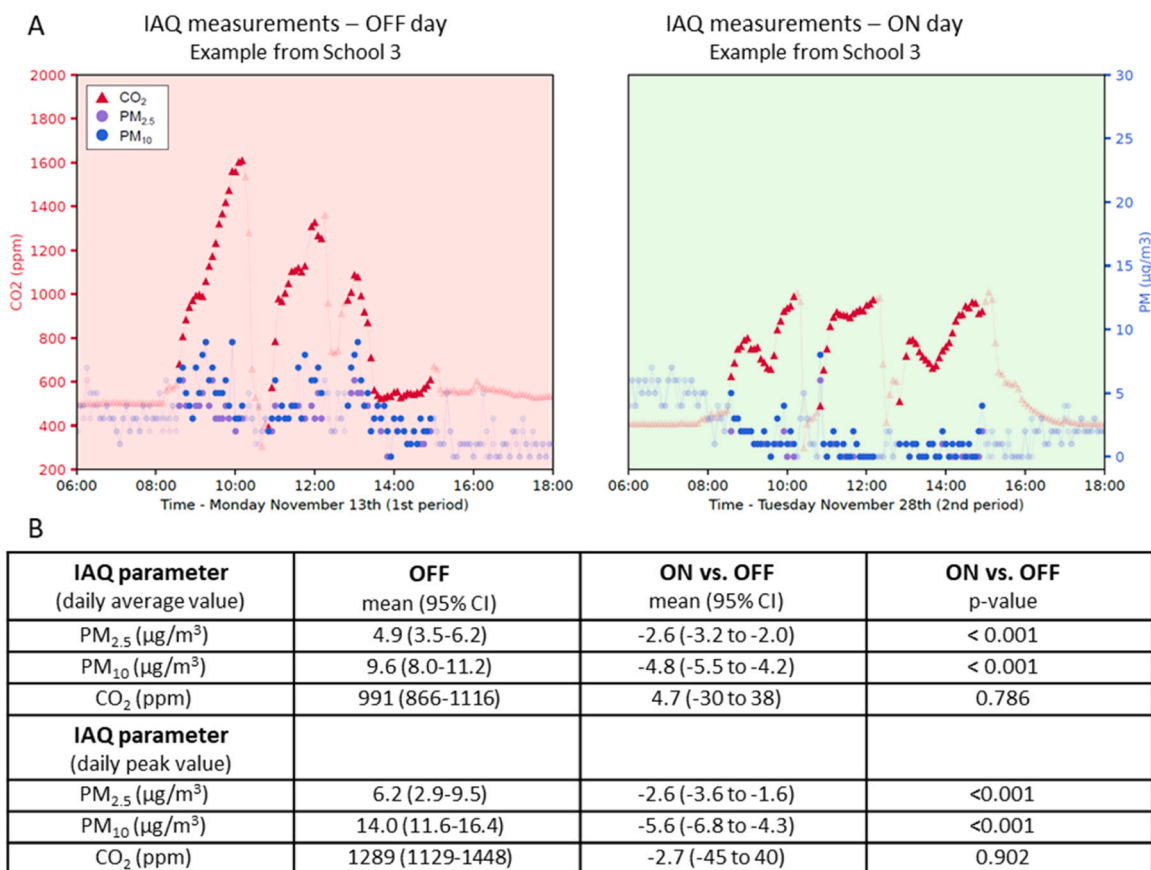


Fig. 2. A) Typical time evolution of IAQ parameters between 06:00 and 18:00 in a classroom of School 3 during the OFF period (left graph; Monday, 13 November 2023) and ON period (right graph; Tuesday, 28 November 2023). CO₂ (ppm) is plotted on the left y-axis and PM_{2.5} and PM₁₀ (µg/m³) on the right y-axis; all axes are shared across both panels. Light-colored data points represent unoccupied periods. B) Estimated effects of MAC operation on daily IAQ concentrations across 15 classrooms, based on linear mixed models with random intercepts for classroom (sensor) and day. The table presents model-estimated average (top) and peak (bottom) concentrations during MAC OFF periods and absolute changes associated with MAC ON, including 95% confidence intervals and corresponding p-values.

comparisons were performed between ON and OFF periods within the same intervention classrooms. For all markers except *S. epidermidis*, inverted Ct values decreased under MAC-on conditions, consistent with the expected reduction in microbial abundance; however, mean differences were generally small and did not reach statistical significance (Table 2). To contextualize these findings, paired comparisons were also performed between the same ON and OFF periods within reference classrooms without MACs, allowing assessment of whether observed changes reflected intervention effects or background temporal variation. In these classrooms, changes in microbial load were observed between periods, with mean differences in a similar range or more extreme than those observed in the intervention classrooms (Table 2).

Perceived feasibility of MAC use

In addition to evaluating the technical performance of MACs, we assessed the perceived feasibility of their use in classrooms through teacher and student surveys and interviews. User-perceived feasibility recognizes that real-world uptake and implementation depends on whether devices can be used, accepted, and integrated into daily school practice. Here, we report on three out of six feasibility domains: acceptability, demand, and implementation. Acceptability covered teacher expectations and overall satisfaction of both teachers and students. At the end of the intervention period, 40% of teachers reported that the MACs met their expectations. During the interviews, administrators and teachers indicated that part of these expectations concerned a reduction of CO₂ levels in classrooms, which MACs cannot address. As one teacher noted: “We have a device that monitors the air quality. Nine

Table 2

Comparison of microbial abundances in intervention and in reference classrooms.

Marker	Intervention classrooms			Reference classrooms		
	ON vs. OFF mean (sd)	Test	p-value	Study period 2 vs. 1 mean (sd)	Test	p-value
16S	-0.31 (1.34)	t	0.16	-0.51 (0.88)	t	0.06
<i>S. salivarius</i>	-0.22 (6.15)	t	0.21	0.73 (4.90)	W	0.56
<i>S. aureus</i>	-1.27 (6.04)	t	0.19	-3.74 (5.99)	t	0.04
<i>S. epidermidis</i>	0.26 (7.06)	t	0.81	-4.03 (5.53)	t	0.02
<i>M. catarrhalis</i>	-0.17 (6.45)	t	0.86	-4.72 (5.33)	W	< 0.01
RSV	-1.72 (8.02)	t	0.18	-2.32 (4.13)	W	0.05

Mean differences are based on inverted Ct values (50 – Ct), with higher values indicating higher abundance to ease interpretation. For the intervention classrooms (ON vs OFF), two samples with 16S measurement with PCR failure were excluded from analysis, resulting in n = 39 pairs for 16S. All other markers had n = 41 pairs. Reference classrooms tests included n = 13 pairs for all markers. t = paired t-test; W = Wilcoxon signed-rank test. Normality was assessed using Shapiro–Wilk tests and the appropriate test was selected accordingly.

out of ten times it’s on red [due to high CO₂ levels]. ... Let’s see if this

helps.” Overall, 25% of teachers reported being satisfied with the MACs (median satisfaction score 3.0, IQR 2.0–3.0). Teachers explained in the interviews that their limited satisfaction was partly related to experiences of increased noise and coldness in classrooms. Among students, 34% rated the MAC as “nice” or “very nice” (median satisfaction score: 3.0, IQR 3.0–4.0) (Fig. 3A). Demand captured willingness to recommend MACs and intent to continue their use. After several weeks of MAC use, only 30% indicated they would likely continue using the devices if they remained in the classroom, and 10% of teachers were likely to recommend their use (Fig. 3B). Implementation focused on ease of use and perceived barriers to correct operation. In the final intervention survey round, most teachers rated the devices as easy to use (64%), though 44% reported difficulties with placement in the classroom (Fig. 3C). Interviewees pointed out their limited rooms for MACs using comments such as: “It’s a big, chunky thing that got in the way quite a bit.”

MAC impact on illness-related school absenteeism

To evaluate the impact of MACs on illness-related absenteeism, we analyzed absence data from all participating schools for the first half of the 2023/24 school year, covering also the MAC intervention period. The overall weekly illness-related absenteeism rate was 0.025 (95% CI: 0.018–0.035) absent days per school day (Fig. 4A), corresponding to an average of 2.27 (95% CI: 1.76–2.90) illness-related absent days per student over the first half of the 2023/24 school year. No significant difference in absenteeism rates was observed between MAC ON and OFF during the 6-week intervention period: estimated rates were 0.039 (95% CI: 0.029–0.053) and 0.038 (95% CI: 0.028–0.051), respectively

(Fig. 4B).

Burden of ARI targetable by MACs

To gain insight into the causes of these absences, 303 completed illness surveys (81.7% response rate) were analyzed. Survey responses indicated that 65.3% of illness-related absences were due to ARI, and 26.4% to GI. Among the ARI cases, 69.7% had no prior household symptoms, suggesting a potential school-related source. Combining the observed absenteeism prevalence during the first half of the 2023/24 school year with the proportion of absences classified as ARI and the proportion without prior household symptoms, we estimated that a maximum of 0.81 (95% CI: 0.61–1.03) school-related ARI absenteeism days per student occurred in this half of the school year, representing the burden potentially targetable by MACs.

Sample size calculation for cluster-randomized trial

To inform the design of a follow-up cluster-randomized trial, we estimated the number of schools required to detect a meaningful reduction in illness-related absenteeism from an intervention such as MAC use in classrooms. Simulations were performed for four scenarios, combining two intervention effect sizes (a 20% or 25% reduction in absenteeism) with two study durations (a full school year or a shorter period from the autumn to the May break). The required number of schools ranged from 40 to 50 (25% reduction over a full vs. shorter school year, respectively) to 70 (20% reduction for both study periods) (Fig. 5).

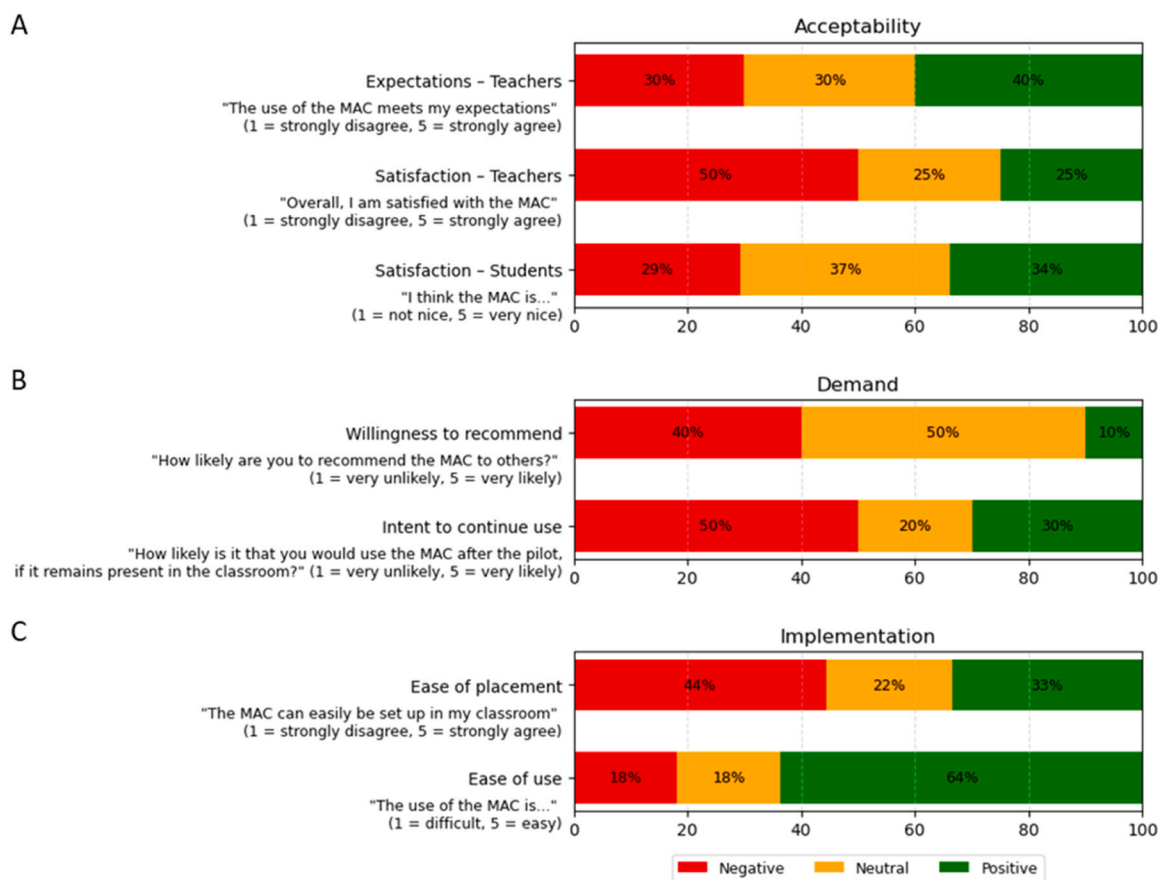


Fig. 3. Summary of survey responses across three domains: A) Acceptability: teacher expectations and overall satisfaction of teachers and students. B) Demand: teachers’ willingness to recommend the MAC to others and their intent to continue using the device if it remained in the classroom. C) Implementation: teachers’ ratings of ease of use and ease of placement of the MAC in their classroom. Percentages of responses are shown, with colors indicating negative (red), neutral (orange), and positive (green).

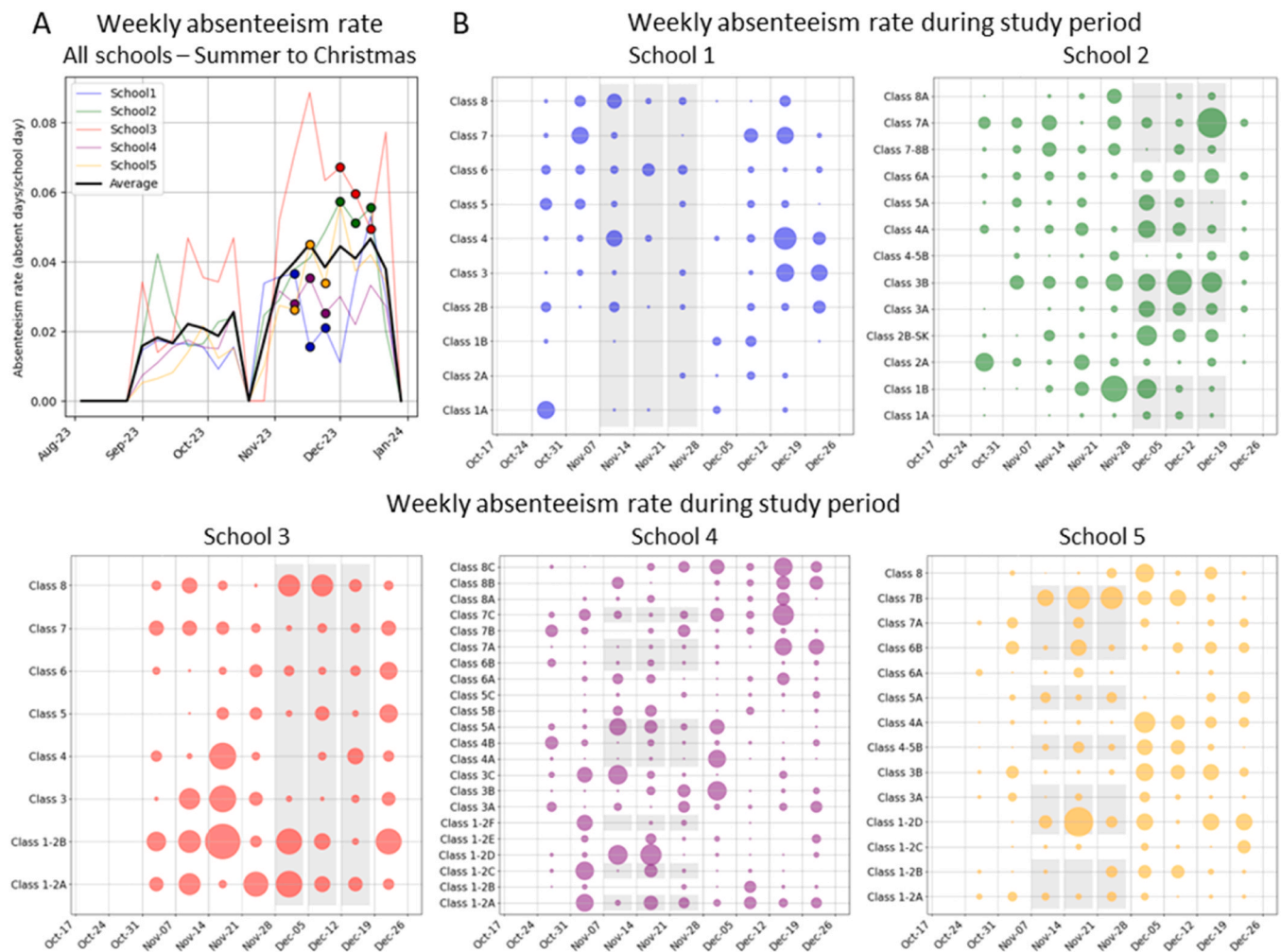


Fig. 4. A) Weekly illness-related absenteeism rates at the school level during the first half of the 2023/24 school year. Each colored line represents an individual school; the black line indicates the average across all schools. ON periods are annotated with dot markers. B) Weekly class-level illness-related absenteeism rates for the same period, shown as circles sized proportionally to the rate. ON periods are indicated by a grey background.

Discussion

This randomized cross-over pilot study was designed as a feasibility-oriented pilot to inform a future large-scale effectiveness trial evaluating the impact of MACs on the transmission of respiratory infections and associated school-absenteeism in primary schools. The study integrated monitoring of generic IAQ parameters and airborne microbial contamination, assessments of perceived feasibility, and analysis of illness-related absenteeism data to inform the design of such a trial. MACs were found to improve IAQ parameters, especially for PM concentrations but less so for airborne microbial load, under real-world conditions. However, feasibility concerns were raised, particularly related to noise levels and space constraints. Analysis of illness-related absenteeism indicated that, on average, students missed just over one day due to school-related acute respiratory illness during the first half of the 2023/24 school year, representing the burden potentially targetable by MACs. Simulation-based power analyses showed that detecting a 20–25% reduction in illness-related absenteeism due to an intervention, would require a cluster-randomized trial involving 40–70 schools.

The IAQ measurements demonstrated that MACs effectively reduced PM concentrations in real-world classroom settings. Concentrations of both PM_{2.5} and PM₁₀ were approximately halved during the MAC ON period compared to the OFF period. These findings align with previous studies demonstrating the potential of MACs to reduce indoor aerosol load [18]. Indoor PM concentrations measured in classrooms reflect a

mixture of particles, including respiratory aerosols and particles originating from indoor and outdoor air pollution [29,30]. The observed reductions therefore reflect general particle removal. Whether such reductions can be translated into a lower risk of infection remains uncertain and would require a substantially larger trial and more measurement points, both indoors and outdoors. Because mobile air cleaners do not remove CO₂, the stable CO₂ levels across the ON and OFF periods, suggest that there were no substantial changes in air exchange conditions or occupancy patterns between the periods [31]. Overall, the observed reductions in PM indicate that the selected MACs performed consistently in the configurations that were recommended.

No clear conclusion on the performance of MAC on airborne microbial load can yet be drawn. Although microbial air concentrations tended to be lower when MACs were operating, a similar trend across sampling periods was observed in reference classrooms without MACs. Outdoor microbial levels are known to vary over time and may be partially reflected indoors [32]. Previous research has also shown that classroom activity can influence airborne microbial loads [33,34]. These and other unaccounted factors may interfere in assessing the technical performance of MACs. As this was a pilot study, we anticipated that the sample size would be insufficient to detect modest reductions against the high background and observed variability. Nevertheless, including microbial sampling yielded valuable insights to inform the design of a larger trial. It highlighted temporal heterogeneity as a relevant factor to consider when choosing trial designs in which microbial contamination

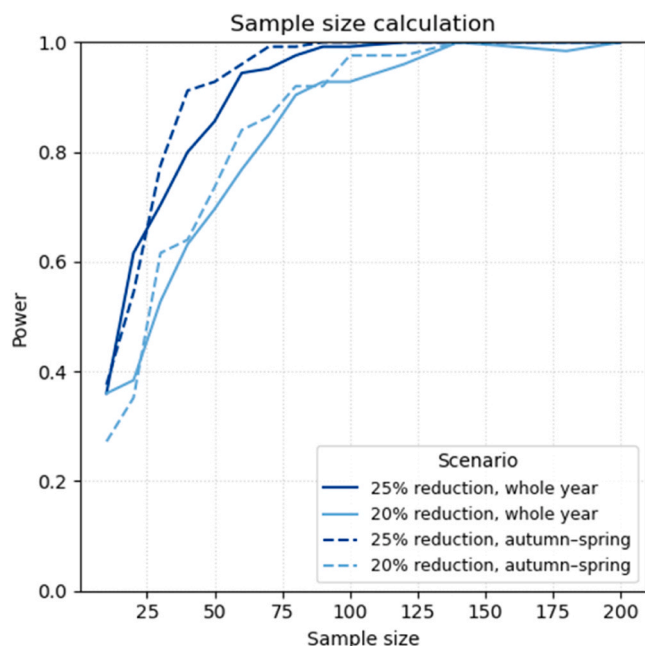


Fig. 5. Estimated number of schools required to detect a reduction in illness-related absenteeism at 80% power, based on simulation results for four scenarios. Scenarios vary by effect size (a 20% or 25% reduction in absenteeism due to the intervention) and study duration (a full school year or a shorter period from the autumn break to the May break).

is assessed.

Our study also revealed major challenges regarding the perceived feasibility of implementing MACs in primary schools. Teachers reported that MACs negatively affected various indicators of environmental comfort, particularly due to noise and cold air drafts, resulting in overall low satisfaction and little intention to use them in the future. In addition, the required positioning of the devices created difficulties in accommodating the devices. While Carmona *et al.* reported generally positive attitudes toward portable air cleaners in U.S. schools, they similarly identified barriers such as noise, limited training, and maintenance concerns that hindered sustained use [19]. These findings have important implications for potential success of implementing MACs in primary school settings and highlight the need to carefully consider their downside effects. Restricting MAC use to high-risk periods, such as during pandemics or epidemics, may help reduce perceived nuisance and improve acceptability; this approach warrants further investigation.

Absenteeism rates did not differ significantly between the MAC ON and OFF periods, which is not unexpected given the limited duration of the intervention (two three-week periods) making it unlikely to detect changes in illness-related absence. Moreover, although MAC use substantially reduced airborne particle levels, it remains unclear to what extent this reduction translates to reduced respiratory infections in classroom settings. Approximately two-third of illness-related absences were attributed to ARI, aligning with evidence that ARI is the leading cause of illness in primary school-aged children [35]. Notably, two-thirds of these absences were not preceded by similar symptoms in the household, suggesting a considerable share may be linked to school-based transmission. This is consistent with established transmission dynamics, where high contact rates and dense indoor interactions facilitate the spread of respiratory viruses in school settings [36,37]. At the same time, illness-related absenteeism also includes conditions unlikely to be affected by air cleaning, which may dilute observable intervention effects. While the overall burden of ARI-related absenteeism during the study period was modest, it still represents a potentially preventable portion of school absence.

Our simulation results indicate that detecting a 20–25% reduction in

illness-related absenteeism would require a cluster-randomized trial including 40–70 schools, which is on the higher end of the sample size range reported in cluster trials using school absenteeism as an outcome measure [38]. The assumed effect size of 20–25% corresponds to approximately one day less illness-related absenteeism per student per year. However, the impact of MACs could be more substantial during periods of heightened respiratory virus circulation, such as during severe seasonal epidemics or pandemics. These findings support the use of school absenteeism as a pragmatic proxy outcome for evaluating interventions targeting respiratory infections.

This study has several strengths. First, it was conducted in operational primary school classrooms across multiple schools, enhancing the real-world relevance of the findings by capturing the variability and constraints typical of everyday school environments. Second, it applied a comprehensive mixed-methods approach, combining IAQ measurements, structured feasibility assessments, and illness-related absenteeism data. This enabled a holistic evaluation of both the technical performance of MACs and their perceived feasibility in school settings. Third, the randomized cross-over design allowed each school to serve as its own control, enabling direct within-school comparisons between MAC ON and OFF conditions while keeping classroom characteristics, such as ventilation type and class size, constant across conditions. This study also has limitations that should be considered when interpreting the findings. First, as a pilot with a short intervention period and no wash-out phase, the design may have allowed residual effects from the MAC ON period to influence the subsequent OFF period. Combined with the small number of participating schools, this limited the statistical power to detect meaningful effects on airborne microbial load and absenteeism and left it unclear to what extent the observed reductions in PM translated into a reduction in respiratory infections. Second, not all contextual factors that may influence indoor air quality, such as classroom-specific ventilation rates and window-opening behavior, were systematically recorded, although CO₂ measurements were included as an indicator of these parameters. In a future large-scale trial, more detailed characterization would further strengthen interpretation of the effects of MACs and allow clearer assessment of their impact across different ventilation conditions. Third, the use of absenteeism as a proxy outcome is pragmatic and relevant for school-based surveillance, but remains an indirect measure of infection. In addition, information on the causes of absence was only collected during a six-week period early in the school year, which may not accurately reflect the proportion of illness-related absenteeism attributable to respiratory infections across the full school year. Third, the study was conducted in Dutch primary schools, and findings on feasibility may not be directly generalizable to other socio-cultural or educational contexts.

Conclusion

This pilot study demonstrated that the selected MACs consistently reduced PM concentrations in the configuration applied in real-world classroom settings, confirming their technical effectiveness. However, teachers reported substantial barriers to implementation, including noise, drafts, and spatial constraints, which may limit their feasibility in daily school practice. Absenteeism appears to be a pragmatic proxy for acute respiratory illness. Simulation results indicated that detecting a 20–25% reduction in absenteeism due to an effective school-based intervention (corresponding to approximately one day less illness-related absenteeism per student per year) would require a cluster-randomized trial involving 40–70 schools. These findings provide a foundation for designing larger trials to evaluate the effectiveness of MACs in reducing respiratory infections in school settings, while also highlighting practical barriers that need to be addressed for successful implementation.

CRedit authorship contribution statement

Clarize de Korne: Formal analysis, Writing – original draft, Writing – review & editing. **Kim Romijnders:** Conceptualization, Investigation, Formal analysis, Writing – review & editing. **Philomena Bluysen:** Conceptualization, Supervision, Writing – review & editing. **Daniel Bonn:** Conceptualization, Supervision, Writing – review & editing. **Er Ding:** Investigation, Formal analysis, Writing – review & editing. **Antoine Gaillard:** Investigation, Formal analysis, Writing – review & editing. **Esmée Janssen:** Formal analysis, Writing – review & editing. **Anne Rittscher-Fogg:** Investigation, Formal analysis, Writing – review & editing. **Inge Wouters:** Conceptualization, Supervision, Writing – review & editing. **Patricia Bruijning-Verhagen:** Funding acquisition, Conceptualization, Supervision, Writing – review & editing.

Consent for publication

Not applicable.

Ethics approval

For the assessment of perceived feasibility through interviews, teachers of students aged nine years and older recruited potential participants and distributed informed consent forms to both students and their parents. Signed consent forms were collected by the school administration and subsequently shared with the research team. Each interview began with a brief introduction of the study, the interview procedures, and a review of the informed consent. This component of the study was reviewed and approved by the Medical Ethical Committee of Utrecht, the Netherlands (23U-0515).

For the remaining components of the study, ethical approval and the requirement to obtain informed consent were waived by the UMC Utrecht internal review board. These components were not subject to the Dutch Medical Research Involving Human Subjects Act (WMO) and did not require approval under the General Data Protection Regulation (GDPR), as no directly identifiable data were used.

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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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Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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