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Protective effect of reduced particulate matter exposure on pulmonary function and cognitive performance among school children: a cross-over trial

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A B S T R A C T

Children spend substantial time in classrooms, where particulate matter (PM) may adversely affect respiratory and cognitive health. However, the incremental health benefits of higher clean air delivery rate (CADR) or multiple air purifiers under real-world classroom conditions remains poorly understood. We evaluated the effects of air purifier CADR and the number of devices on PM reduction, pulmonary function, airway inflammation, and cognitive performance in schoolchildren. Period crossover intervention trial was conducted over 6 weeks in three classrooms, involving 66 children aged 8–9 years. Participants underwent three 1-week intervention conditions: 1) two devices with a CADR of 520 m^3/h (higher-CADR/multiple condition), 2) one device with a CADR of 400 m^3/h (lower-CADR/single condition), and 3) two devices with a CADR of 400 m^3/h (lower-CADR/multiple condition), each separated by a 1-week washout. PM concentrations were monitored during school hours. Pulmonary function, fractional exhaled nitric oxide (FeNO), and cognitive attention scores were assessed before and after each intervention period. Linear mixed-effects models with false discovery rate correction were used to estimate intervention effects and the associations between PM reduction and health outcomes. In condition-specific analyses, only the higher-CADR/multiple condition was associated with significant improvements in cognitive performance, except for particle number concentration. In contrast, the lower-CADR/single condition was associated with significant reductions in FeNO across all PM size fractions. In between-condition comparisons, the FeNO reduction associated with an interquartile range decrease in $PM_{1.0}$ was significantly greater under the lower-CADR/single condition than under the higher-CADR/multiple condition by 29.4% (95% CI: 7.8–55.2%). In pooled analyses across intervention conditions, each interquartile-range reduction in PM was associated with improvements in all health outcomes except forced vital capacity. Higher-capacity air purification may provide greater benefits for children's cognitive performance and pulmonary function, whereas lower-capacity systems may be sufficient to reduce airway inflammation in school settings.

1. Introduction

Ambient particulate matter (PM) is a well-documented contributor to various health conditions. The Global Burden of Disease study linked short-term exposure to $PM_{2.5}$ with approximately one million premature deaths, accounting for 2.08% of global mortality (Yu et al., 2024). Children are particularly vulnerable to particulate matter exposure. Particulate matter has been shown to increase airway inflammatory markers and reduce pulmonary function in children (Barraza-Villarreal et al., 2008). Also, particulate matter can reach the developing brain through the olfactory pathway or systemic circulation, induce neuroinflammation, and impair cognitive function (Calderón-Garcidueñas et al., 2011). Given that people spend over 80% of their day indoors, indoor PM exposure is just as critical as outdoor exposure (Klepeis et al., 2001). Even at low concentrations, indoor PM exposure can still have detrimental health effects, highlighting the importance of indoor PM (Di

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et al., 2017).

It is well known that air purifiers are effectively reducing indoor PM exposure. Several studies have consistently demonstrated significant reductions in indoor PM concentrations, regardless of the air purifier types (Guo et al., 2021; Liu et al., 2021). In addition, use of air purifiers has shown significant improvement of surrogate biomarkers for cardio-respiratory diseases (Chen et al., 2015). However, prior studies primarily examined the effectiveness of a single air purifier installed in a specific indoor space by alternating between real purification (filter turned on) and sham purification (filter off or not used). Especially for children, exposure to lower particulate matter (PM) concentrations may provide potential benefits for pulmonary function and cognitive performance (Gauderman et al., 2015; Sunyer et al., 2015). Therefore, implementing air purifiers with higher clean air delivery rates (CADRs) and using multiple devices in the same indoor space may be a more effective approach.

In Korea, children usually spend most of their daily and weekly time at school (Yoon et al., 2020). Since 2019, every classroom especially in Seoul has been installed with a single air purifier, ensuring a CADR of at least 780 m^3/h as mandated by the Ministry of Education's School Health Act. However, the sufficiency of a single air purifier in classrooms is still ambiguous to improve student health outcomes. Considering the vulnerability of children, the removal of PM in classrooms and improvement of health effects need to be investigated by different CADRs and the number of air purifiers.

Therefore, we aimed to investigate the effect of different CADRs and the number of air purifiers in school children by: 1) monitoring indoor PM concentrations in all air purifier adjustment scenarios; 2) examining improvements in pulmonary function and cognitive performance across different scenarios; This will provide new insights into air purifier interventions for susceptible populations.

2. Materials and methods

2.1. Study design and participants

This cross-over study was conducted from October 2022 to July 2023 in an elementary school in Seoul, South Korea. The sample size was estimated based on forced expiratory volume in 1 s (FEV1) as the primary continuous outcome. For the 3-treatment, 3-period crossover design, PASS software was used to calculate the required sample size under a Geisser–Greenhouse corrected F-test. The calculation assumed a target power of 80%, a two-sided Type I error rate of 0.05, and a within-subject correlation of 0.6. The within-period standard deviation of FEV1 was conservatively set at 0.03 L based on Dong et al. (2019), and the standard deviation among the three treatment-condition means was assumed to be 0.5 based on previous repeated-measures and crossover studies (Chen et al., 2015; Shan et al., 2020). The required sample size was estimated to be 54 participants. Considering a 20% potential dropout rate, 66 participants were enrolled, all of whom completed the study. The inclusion criteria were: 1) age 7–8 years, 2) living a designed residential area to public elementary school for at least 1 year, and 3) no plans to transfer to another school during the study period.

The study protocol was approved by the Institutional Review Board of Yonsei University Health System (4-2019-1231). All study procedures adhered to the tenets of the Declaration of Helsinki. Written informed consent was obtained from all participants and their parents/guardians. This study was registered with the Clinical Research Information Service established at the Korea Disease Control and Prevention Agency with support from the Ministry of Health and Welfare (PRE20230608-003).

2.2. Air purifier intervention

The interventions were conducted in three classrooms: the first trial (from November to December 2022) and the second trial (from May to June 2023) over 12 weeks. The air purifiers were installed 1.2 m above ground, equal to the children's breathing zone. To evaluate the adequacy of the classroom CADR of 780 m^3/h recommended by the Korean Ministry of Education, three treatment scenarios were considered Three treatment scenarios were considered: 1) two air purifiers with 520 m^3/h CADR defined as the higher-CADR/multiple condition (higher-CADR/MC), 2) one air purifier with 400 m^3/h CADR defined as the lower-CADR/single condition (lower-CADR/SC), and 3) two air purifiers with 400 m^3/h CADR defined as the lower-CADR/multiple condition (lower-CADR/MC). All devices were equipped with H13 grade HEPA filters capable of removing 99.95% of 0.3 μm PM size. One device was placed on a bookshelf at the back of the classroom and the second purifier was placed on a bookshelf near a window facing the playground.

The air purifier intervention design is shown in Fig. 1. During the first week, we measured the background concentration of PM in each classroom. From week 2 to week 6, intervention and wash-out were alternated for one week each. A 1-week washout period was determined based on evidence of acute and reversible recovery of pulmonary function and airway inflammation following low-to-moderate pollutant exposure (Leikauf et al., 2020), as well as temporal variability in ambient particulate matter, temperature, and humidity during the study period (Allabakash et al., 2022). In contrast, cognitive performance assessed using the brain-training platform may be subject to longer-term carryover effects, which does not necessarily follow the same physiological pattern as pulmonary function and airway inflammation. Accordingly, play number was adjusted for to account for learning (or practice) effects across successive assessments (Goldberg et al., 2015). The intervention was conducted Monday to Friday between 09:00 a.m. and 01:00 p.m. to align with the school schedule. During the intervention, windows facing the playground were kept closed. Doors facing the hallway were closed during class but opened during breaks. A total of six measurements of clinical parameters and PM concentrations were obtained before and after air purifier operation.

2.3. PM measurements

All measurement devices were installed 1.2 m above the floor to reflect a practical classroom breathing-zone height across typical seated and ambulatory activities and were positioned at the back of the classroom to avoid disrupting instruction. Given that the classroom measured 9 m in width and 7.5 m in length, we considered that placing the instruments away from the center of the room would still provide sufficient representativeness of the indoor environment. PM_{10}, $PM_{2.5}$, $PM_{1.0}$, and total particle number concentration (PNC) were measured from 09:00 a.m. to 01:00 p.m. with 1-min intervals. All PMs were monitored by a portable Aerosol Spectrometer 11-D (GRIMM Aerosol Technik, Hamburg, Germany). Class-level ambient PM was measured near the 1 or 2 representative homes per class to capture after-school outdoor effects. Given that all participants lived within approximately 800 m of the school and in similar residential settings, any exposure misclassification was likely to be non-differential.

2.4. Health outcome measurements

Before the intervention study, face-to-face surveys were conducted with schoolchildren and their parents or guardians to collect baseline information, including demographic characteristics (height, weight, age, and sex), home environment (type of residence, daily cooking frequency, daily cleaning frequency, and use of air purifiers), household smoking status, physical activity involving sweating, and parent-reported medical history of physician-diagnosed asthma, allergic rhinitis, atopic dermatitis, and pediatric psychiatric disorders. Health outcomes were measured by a trained nurse on both Mondays (09:00–11:00 a.m.) and Fridays (10:30 a.m.–12:30 p.m.) of each intervention week. To minimize investigator bias, all researchers were trained and assigned to specific health measurements until the end of the intervention.

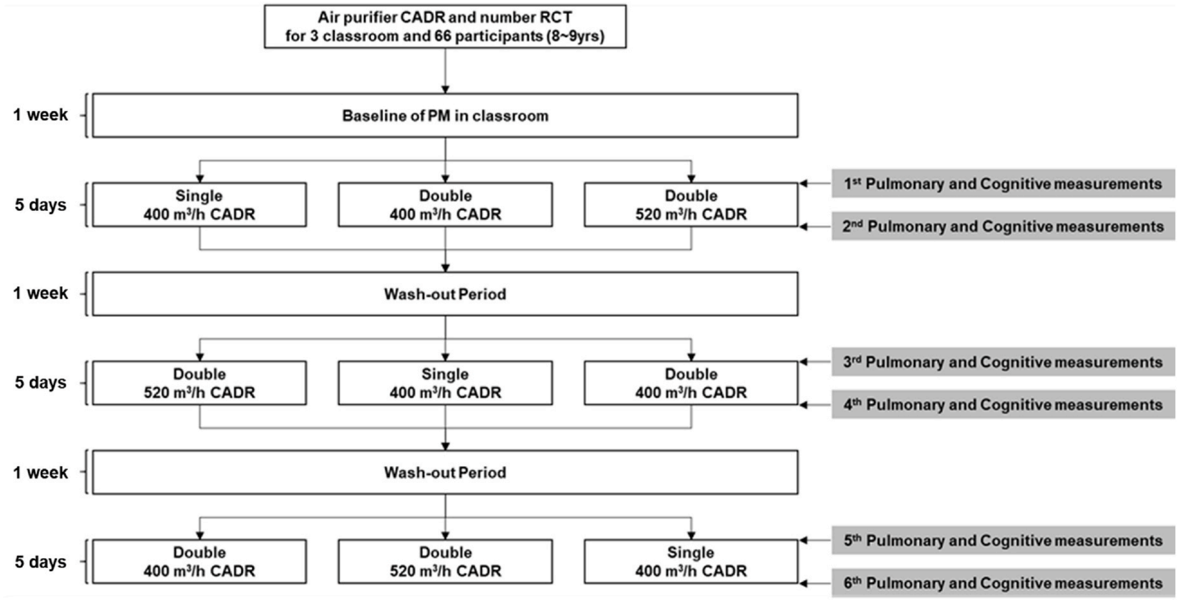

Fig. 1. The scheme of air purifier intervention study. Abbreviations: CADR, clean air delivery rate; RCT, randomized crossover trial.

2.5. Pulmonary function evaluation

Pulmonary tests were performed inside the classroom. Levels of fractional exhaled nitric oxide (FeNO), as an indicator of airway inflammation, were measured using a NOBreath machine (Bedfont Scientific Ltd, UK) following the American Thoracic Society (ATS) guidelines (Dweik et al., 2011). The FeNO levels were compared against ATS guideline cutoff points (Table S1) (Dweik et al., 2011). Pulmonary function was assessed using a microQuark spirometer (COSMED, Italy) following the ATS/European Respiratory Society recommendations. Evaluated parameters included forced vital capacity (FVC), forced expiratory volume in 1 s (FEV1), FEV1/FVC, forced mid-expiratory flow (FEF25−75%), and peak expiratory flow (PEF). Each parameter was measured at least three times for each participant, and the mean of the three closest values was used for data analysis.

2.6. Cognitive performance evaluation

The evaluation of cognitive performance was conducted among the children who participated in the second intervention by utilizing the "Lost in Migration" game on the Lumosity brain-training platform (Lumos Labs, Inc., U.S.). This game was designed based on the Eriksen flanker task to assess selective attention (the ability to focus on target information while ignoring distractions) and response inhibition (the ability to suppress responses to distractions). In the game, five birds fly in different directions (right, left, up, or down). The task is to drag a finger on the screen in the direction indicated by the bird in the center. The other four birds may point in the same or different directions.

In this study, we interpreted point variations as an attention score related to cognitive performance. All participants completed the test using a Samsung Galaxy Z Fold3 smartphone while seated in a designated position, with the device placed on a desk and using only the index fingers of right hand (Fig. S2).

2.7. Statistical analysis

Continuous clinical and environmental variables were summarized using descriptive statistics. Paired Student's t-tests were used only for preliminary within-type comparisons between pre- and post-intervention measurements. The primary analyses were conducted using linear mixed-effects models. Natural logarithm transformation was applied to outcome variables to reduce skewness and improve the normality and homoscedasticity of residuals (Fig. S1). Under this specification, estimated coefficients were interpreted on a multiplicative scale and converted to percentage changes using $100 \times [\exp(\beta) - 1]$.

All mixed-effects models included a subject-specific random intercept to account for repeated measurements within participants. A first-order autoregressive [AR(1)] correlation structure was specified to account for within-subject autocorrelation across repeated measurement times (Goldberg et al., 2015). Covariates included age, sex, history of disease, presence of pets, use of air purifiers at home, cleaning frequency at home, presence of a smoker at home, sweat-inducing regular physical activity, and temperature-humidity. Trial or play number was included as a fixed-effect covariate to account for potential learning or repeated-testing effects in pulmonary and cognitive assessments.

First, specific effects were estimated separately for each air purifier type as following model:

$$\ln Y_{it} = \beta_0 + \beta_1 Intervention_a + \beta_2 x_2 + \cdots + \beta_p x_p + u_i + \varepsilon_{it} \tag{1}$$

To estimate the association between indoor PM concentration and health outcomes within each air purifier type, we fitted the following model:

$$\ln Y_{it} = \beta_0 + \beta_1 Indoor\_PM_a + \beta_2 x_2 + \cdots + \beta_p x_p + u_i + \varepsilon_{it} \tag{2}$$

In these formulas, '*i*' represents the subject, '*t*' indicates the trial numbers (1 to 6), '*a*' denotes each air purifier categorized by CADR and the number of devices, Y_{it} is the logarithm of outcome parameters in subject *i* at time *t*, β_0 is the overall intercept, $intervention_a$ is a binary variable coded as 0 for baseline and 1 for post-intervention measurements, $Indoor\_PM_a$ denotes the particulate matter concentration in the classroom, x_2-x_p are covariates, u_i is the specific random intercept for subject *i*, and ε_{it} is the residual error for subject *i* at time *t*.

To compare specific effect estimates across air purifier type, we conducted post hoc comparative effect testing. Linear mixed-effects models were fitted separately for each air purifier type, and the estimated coefficients were compared between types using Z-tests. The difference between two estimates was calculated as $Q_1 - Q_2$, and its standard error was calculated as $\sqrt{SE_1^2 + SE_2^2}$. Two-sided p-values were obtained from the standard normal distribution. These analyses were interpreted as comparative effect testing.

Second, to estimate the overall intervention effect across all air purifier types, we conducted pooled analyses using all measurements irrespective of air purifier types. Air purifier type was additionally included as a random intercept:

$$\ln Y_{it} = \beta_0 + \beta_1 Intervention_{all\ types} + \beta_2 x_2 + \cdots + \beta_p x_p + u_a + u_i + \varepsilon_{ait} \quad (3)$$

Similarly, to estimate the overall association between indoor PM and health outcomes across all air purifier types, we fitted the following:

$$\ln Y_{it} = \beta_0 + \beta_1 Indoor\_PM_{all\ types} + \beta_2 x_2 + \cdots + \beta_p x_p + u_a + u_i + \varepsilon_{ait} \quad (4)$$

u_a, which is the specific random intercept for the air purifier type a, was additionally included to account for variability between air purifier types. $Intervention_{all\ types}$ was defined irrespective of air purifier type, with 0 assigned to measurements obtained before air purifier operation and 1 assigned to measurements obtained after air purifier operation. $Indoor\_PM_{all\ types}$ denotes all classroom particulate matter concentrations measured before and after air purifier operation, regardless of air purifier type. Finally, to evaluate whether the associations between indoor PM and health outcomes were robust to outdoor PM exposure, outdoor PM was additionally adjusted for in Model 4.

All PM effects were expressed as percentage changes in outcome measurements associated with an interquartile range (IQR) decrease in PM concentration. The IQR values used in the analysis were 10.9 μg/m^3 for PM_{10}, 9.7 μg/m^3 for $PM_{2.5}$, 8.7 μg/m^3 for $PM_{1.0}$, and 132.9 particles/cm^3 for PNC.

To address the increased risk of type I error due to multiple comparisons, false discovery rate (FDR) correction was applied. For condition-specific intervention and PM analyses, FDR correction was applied within each exposure-specific family of outcome tests. For post hoc comparative effect testing between air purifier types, FDR correction was applied within each exposure- and contrast-specific family of outcome tests. For combined and outdoor PM-adjusted analyses, FDR correction was applied separately within each exposure-specific family of outcome tests. Both nominal p-values and FDR-corrected p-values were reported. Results with nominal $p < 0.05$ but FDR-corrected $p \geq 0.05$ were interpreted as exploratory, and results with confidence intervals including the null were not interpreted as statistically significant.

All mixed-effects models were fitted using the nlme package in R software (version 4.1.3; R Foundation for Statistical Computing, Vienna, Austria).

Table 1
Demographic characteristics of the study participants.

Variables	Descriptive statistics
Height (cm), mean (SD)	129.2 (5.7)
Weight (kg), mean (SD)	17 (63.1)
BMI (kg/m^2), mean (SD)	17.4 (2.8)
Age (year), mean (SD)	8.8 (0.4)
Sex, N (%)	
Male	34 (51.5%)
Female	32 (48.5%)
History of disease, N (%)	
No	64 (97.0%)
Yes	2 (3.0%)
Presence of pets, N (%)	
No	54 (81.8%)
Yes	12 (18.2%)
Use of air purification system in the home, N (%)	
No	24 (36.4%)
Yes	42 (63.6%)
Frequency of indoor cleaning per day in the home, N (%)	
Less than once	42 (63.6%)
Once	19 (28.9%)
Twice	4 (6.1%)
Three times or more	1 (1.5%)
Presence of a smoker in the home, N (%)	
No	64 (97.0%)
Yes	2 (3.0%)
Sweat-inducing regular workouts, N (%)	
No	12 (18.2%)
Yes	54 (81.8%)

Abbreviations: SD, standard deviation; BMI, body mass index.

3. Results

3.1. Participants' characteristics

Of the total 66 participants in three classrooms, 39 participated in the first round of the intervention and 27 in the second round. Participants were either 8 or 9 years old, with a mean age of 8.8 ± 0.4 years. The average body mass index was 17.4 ± 2.8 kg/m^2. Two participants had a history of chronic disease, and none lived with smokers. A total of 42 participants reported using air purifiers at home. Fifty-four participants (81.8%) engaged in physical activities intense enough to cause sweating (Table 1).

3.2. Environmental and health outcomes

Table 2 shows the changes in PM concentrations and health outcomes following pooled analysis of all air-purifier interventions.

Table 2
Comparison of particulate matter and health outcomes between baseline and post-intervention after pooled analysis of all air purifier interventions.

Variables	Baseline	Post-intervention	Mean difference	Paired *t*-test p-value
	Mean (SD)			
Particulate matter				
PM_{10} (μg/m^3)	28.96 (11.57)	13.58 (6.44)	−15.38	<0.001*
$PM_{2.5}$ (μg/m^3)	17.55 (7.04)	6.72 (3.48)	−10.83	<0.001*
$PM_{1.0}$ (μg/m^3)	13.23 (5.30)	4.37 (2.26)	−8.86	<0.001*
Total PNC (#/cm^3)	173.26 (66.34)	58.34 (40.74)	−120.92	<0.001*
Pulmonary				
FVC (L)	1.67 (0.43)	1.68 (0.37)	0.01	0.587
FEV1 (L)	1.28 (0.34)	1.36 (0.32)	0.08	<0.001*
FEV1/FVC (%)	77.94 (16.34)	82.05 (12.90)	4.28	0.006*
FEF25-75% (L/s)	1.22 (0.63)	1.47 (0.66)	0.25	<0.001*
PEF (L/min)	2.27 (0.82)	2.71 (0.92)	0.44	<0.001*
FeNO (ppb)	14.27 (9.10)	13.06 (8.78)	−1.19	0.019*
Cognitive performance				
Attention score	8,391 (2,938)	10,282 (2,222)	1891	<0.001*

Note: (After school) Outdoor average and standard deviation of PM: PM_{10} 22.09 (9.06) μg/m^3, $PM_{2.5}$ 16.46 (5.93) μg/m^3, $PM_{1.0}$ 13.38 (4.82) μg/m^3, and total PNC 191.54 (88.56) #/cm^3. *$p < 0.05$. Abbreviations: PM_{10}, particulate matter with an aerodynamic diameter ≤10 μm; $PM_{2.5}$, particulate matter with an aerodynamic diameter ≤2.5 μm; $PM_{1.0}$, particulate matter with an aerodynamic diameter ≤1 μm; PNC, particle number concentration; FVC, forced vital capacity; FEV1, forced expiratory volume in 1 s; FEF, forced expiratory flow; PEF, peak expiratory flow; FeNO, fractional exhaled nitric oxide; SD, standard deviation.

Significant reductions in PM concentrations and improvements in several health outcomes were observed after the intervention. PM concentrations decreased by approximately 54.2–67.0%, all pulmonary function parameters, except FVC, significantly improved (6.3–20.5%), and the attention score improved by 22.5%.

The PM concentrations and health outcomes before and after the intervention according to the CADR and the number of devices are presented in Table S2. The baseline PM concentrations were similar across the intervention periods. After the intervention, the classroom with the higher-CADR/MC showed a marked reduction in PM levels, although the difference from other purifiers was not substantial. Among health outcomes, no significant change from baseline was found for FVC after the intervention. However, significant improvements were observed in FEF25–75%, PEF, and attention scores under CADR conditions. The potential influence of the outdoor PM level reduction during air-purifier intervention was examined (Table S3). A statistically significant difference was observed between indoor and outdoor PM levels prior to intervention, whereas this disparity increased substantially following intervention.

Fig. 2 shows the time-series changes in PM levels according to the CADR and number of devices. Before the intervention, the baseline PM concentrations were similar across different CADRs. After the air purifiers were turned on, PM levels decreased markedly, although a transient increase was observed during recess. PM levels increased again after the end of classes, when the purifiers were turned off. Indoor PM concentrations remained lower than outdoor PM concentrations except during dismissal.

3.3. Intervention effects by each air purifier type

We evaluated associations of different intervention scenarios with environmental and health outcomes. PEF significantly improved in the higher-CADR/MC and the lower-CADR/MC, whereas only the higher-CADR/MC improved FEV1/FVC, FEF25–75%, and cognitive performance, and lower-CADR/SC reduced airway inflammation (Table S4). An IQR decrease in PM_{10} and $PM_{2.5}$ was significantly associated with PEF across all intervention scenarios, whereas only the higher-CADR/MC improved FEV1, FEV1/FVC, FEF25–75%, and cognitive performance. Airway inflammation was significant only under the lower-CADR/SC (Table S5 and S6). However, the higher-CADR/MC was associated only with improvements in FEV1/FVC, FEF25–75%, PEF and cognitive performance, whereas the lower-CADR/SC was effective only in improving airway inflammation (Table S7). Only under the higher-CADR/MC, FEV1/FVC, FEF25-75%, PEF showed statistically significant improvements in both the intervention effect and across all particle-size fractions (Table S4–S8). FeNO reduction under the lower-CADR/SC was consistently observed across the intervention-effect and PM-based analyses (Table S4–S8). The attention score was a significant health parameter in the higher-CADR/MC, whereas no significant association was observed under the lower-CADR/SC (Table S4–S8).

3.4. Post hoc comparative effect testing across air purifier types

We further examined the differences in airway inflammation and cognitive performance related to reductions in PM concentrations by air purifier CADRs and the number of devices (Table 3). In analyses excluding the overall intervention effect, only the lower-CADR/SC showed significantly greater reductions in FeNO than the higher-CADR/MC, satisfying both the nominal p-value and FDR-corrected p-value criteria for $PM_{1.0}$ (29.4%, 95% CI: 7.8–55.2%; p-value = 0.006; FDR-corrected p-value = 0.039). Within the same intervention comparison, the nominal p-values for PM_{10}, $PM_{2.5}$, and PNC were below the 0.05 threshold, but they did not remain statistically significant after FDR correction: PM_{10} (16.4%, 95% CI: 3.2–31.3%; p-value = 0.014; FDR-corrected p-value = 0.097), $PM_{2.5}$ (22.1%, 95% CI: 4.3–42.9%; p-value = 0.013; FDR-corrected p-value = 0.091), and PNC (33.8%, 95% CI: 7.4–66.6%; p-value = 0.009; FDR-corrected p-value = 0.065).

Cognitive performance did not show statistically significant differences across air purifier conditions at the 0.05 significance level. Based on a nominal p-value threshold of 0.10, suggestive differences were

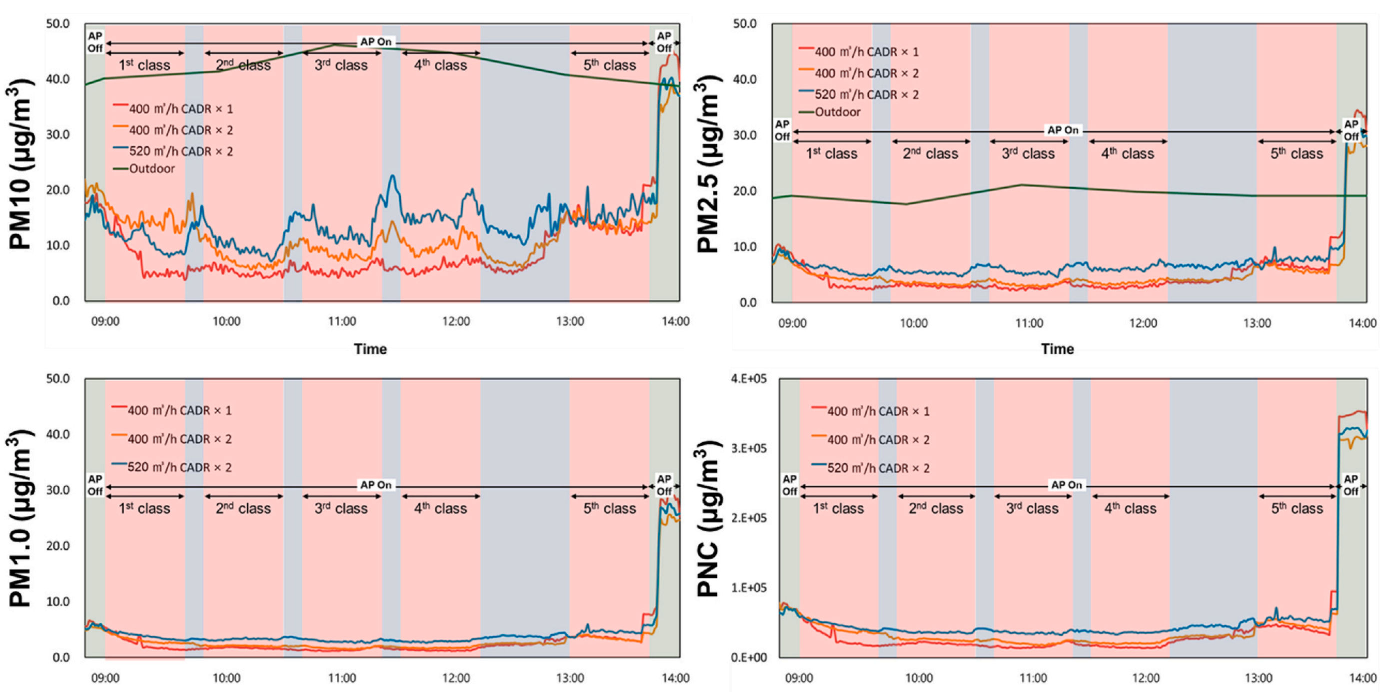

Fig. 2. Time-series of particulate matter concentration during class hours. Outdoor PM_{10} and $PM_{2.5}$ were from nearest national ambient monitoring site. $PM_{1.0}$ and PNC (particle number concentration) were not measured at the national ambient monitoring site; therefore, these metrices are not displayed in the figure. Abbreviations: PM_{10}, particulate matter with an aerodynamic diameter ≤10 μm; PM_{10}, particulate matter with an aerodynamic diameter ≤10 μm; $PM_{2.5}$, particulate matter with an aerodynamic diameter ≤2.5 μm; $PM_{1.0}$, particulate matter with an aerodynamic diameter ≤1 μm; PNC, particle number concentration.

Table 3
Statistical differences in airway inflammation and cognitive performance associated with IQR decreases in PM across air purifier types and device numbers.

Variables	Air purifier difference (CADR, N)	%	(95% CI)	Z-test p-value	FDR corrected Z-test p-value
Intervention effect					
FeNO (ppb)	(400, 2) vs (400, 1)	9.9	(-11.4, 36.2)	0.391	0.921
	(520, 2) vs (400, 2)	9.7	(-12.8, 37.8)	0.429	0.601
	(520, 2) vs (400, 1)	20.5	(-4.8, 52.4)	0.120	0.395
CP	(400, 2) vs (400, 1)	7.8	(-12.1, 32.0)	0.471	0.921
	(520, 2) vs (400, 2)	11.6	(-11.4, 40.6)	0.352	0.601
	(520, 2) vs (400, 1)	20.3	(-1.7, 47.1)	0.073	0.395
PM_{10}					
FeNO (ppb)	(400, 2) vs (400, 1)	5.0	(-6.4, 17.8)	0.406	0.925
	(520, 2) vs (400, 2)	10.8	(-1.6, 24.8)	0.089	0.311
	(520, 2) vs (400, 1)	**16.4**	**(3.2, 31.3)**	**0.014***	**0.097**
CP	(400, 2) vs (400, 1)	2.9	(-12.9, 21.6)	0.734	0.925
	(520, 2) vs (400, 2)	39.1	(-3.5, 100.5)	0.077	0.311
	(520, 2) vs (400, 1)	43.2	(-0.7, 106.3)	0.054	0.190
$PM_{2.5}$					
FeNO (ppb)	(400, 2) vs (400, 1)	9.2	(-5.5, 26.3)	0.233	0.992
	(520, 2) vs (400, 2)	11.8	(-4.9, 31.4)	0.177	0.492
	(520, 2) vs (400, 1)	**22.1**	**(4.3, 42.9)**	**0.013***	**0.091**
CP	(400, 2) vs (400, 1)	0.7	(-16.3, 21.3)	0.937	0.992
	(520, 2) vs (400, 2)	29.1	(-5.6, 76.4)	0.109	0.492
	(520, 2) vs (400, 1)	30.0	(-4.9, 77.7)	0.100	0.349
$PM_{1.0}$					
FeNO (ppb)	(400, 2) vs (400, 1)	9.4	(-6.6, 28.1)	0.265	0.986
	(520, 2) vs (400, 2)	18.3	(-2.5, 43.4)	0.088	0.241
	(520, 2) vs (400, 1)	**29.4**	**(7.8, 55.2)**	**0.006***	**0.039***
CP	(400, 2) vs (400, 1)	2.5	(-14.6, 22.9)	0.793	0.986
	(520, 2) vs (400, 2)	26.8	(-4.8, 68.9)	0.104	0.241
	(520, 2) vs (400, 1)	29.9	(-2.2, 72.6)	0.070	0.169
PNC					
FeNO (ppb)	(400, 2) vs (400, 1)	17.5	(-2.6, 41.7)	0.093	0.621
	(520, 2) vs (400, 2)	13.9	(-7.1, 39.6)	0.211	0.295
	(520, 2) vs (400, 1)	**33.8**	**(7.4, 66.6)**	**0.009***	**0.065**
CP	(400, 2) vs (400, 1)	8.3	(-10.4, 31.0)	0.409	0.649
	(520, 2) vs (400, 2)	5.8	(-16.0, 33.4)	0.632	0.632
	(520, 2) vs (400, 1)	14.6	(-9.4, 45.1)	0.256	0.561

Note: (520, 2) is the higher-CADR/MC, (400, 2) is the lower-CADR/MC and (400, 1) is the lower-CADR/SC. Abbreviations: CADR, clean air delivery rate; PM_{10}, particulate matter with an aerodynamic diameter ≤10 μm; $PM_{2.5}$, particulate matter with an aerodynamic diameter ≤2.5 μm; $PM_{1.0}$, particulate matter with an aerodynamic diameter ≤1.0 μm; PNC, particle number concentration; CI, confidence interval; FeNO, fractional exhaled nitric oxide; CP, cognitive performance. *$p < 0.05$.

observed between the higher-CADR/MC and the lower-CADR/SC. however, these differences were not supported by the FDR-corrected p-values: intervention effect (20.3%, 95% CI: −1.7–47.1%; p-value = 0.073; FDR-corrected p-value = 0.395), PM_{10} (43.2%, 95% CI: −0.7–106.3%; p-value = 0.054; FDR-corrected p-value = 0.190), $PM_{2.5}$ (30.0%, 95% CI: −4.9–77.7%; p-value = 0.100; FDR-corrected p-value = 0.349), and $PM_{1.0}$ (29.9%, 95% CI: −2.2–72.6%; p-value = 0.070; FDR-corrected p-value = 0.169).

Regarding pulmonary outcomes, the difference in FEV1/FVC associated with PNC reduction between the higher-CADR/MC and the lower-CADR/MC was nominally significant at 9.9% (95% CI: 0.5–20.2%; p-value = 0.039), but did not remain significant after FDR correction (FDR-corrected p-value = 0.188) (Table S9–S13).

3.5. Pooled effects across all air purifier types

Finally, we assessed the overall health improvement effects of the air purifier intervention. As shown in Fig. 3, all health outcomes except FVC showed statistically significant improvements according to both nominal p-values and FDR-corrected p-values. For example, an IQR decrease in $PM_{2.5}$ was associated with improvements in FEV1 (2.7%, 95% CI: 1.3–4.1%), FEV1/FVC (3.4%, 95% CI: 1.2–5.7%), FEF25–75% (4.9%, 95% CI: 2.0–7.9%), PEF (7.1%, 95% CI: 4.5–9.7%), FeNO (−5.5%, 95% CI: −10.0 to −0.7%), and attention score (12.0%, 95% CI: 3.0–21.9%) (Table S14 and S15). The results remained consistent even after adjusting for after-school outdoor PM exposure.

4. Discussion

In this study, we assessed the effectiveness of air purifier interventions with varying CADRs and device numbers in reducing PM concentration and improving health outcomes in children. Our findings demonstrated that PEF improved regardless of the air purifier type. Furthermore, the higher-CADR/MC was associated with greater improvement in cognitive performance than the other purifier types, except for the decrease in PNC. Surprisingly, the lower-CADR/SC demonstrated the greatest reduction in airway inflammation. Regardless of air purifier type, the analysis of the overall average effect showed statistically significant improvements in all health outcomes except FVC, with smaller particle sizes being associated with more pronounced health benefits.

Our study demonstrated that even short-term use of air purifiers in classroom was associated with improvements in children's pulmonary function. Improvements were obvious in all parameters (FEV1, FEV1/FVC, PEF, and FEF25-75%) except FVC. Consistent with our findings, previous studies have reported significant improvements in FEV1 and PEF in children following air purifier interventions in classrooms (Kouis et al., 2024), and also shown positive effects of short-term air purifier use on pulmonary function (S. Kim et al., 2020). While our study showed a significant reduction in airway inflammation after intervention, aligning with randomized controlled trials involving air purifier use in children (Dong et al., 2019), another study, despite demonstrating significant improvements in asthma control test, did not find significant

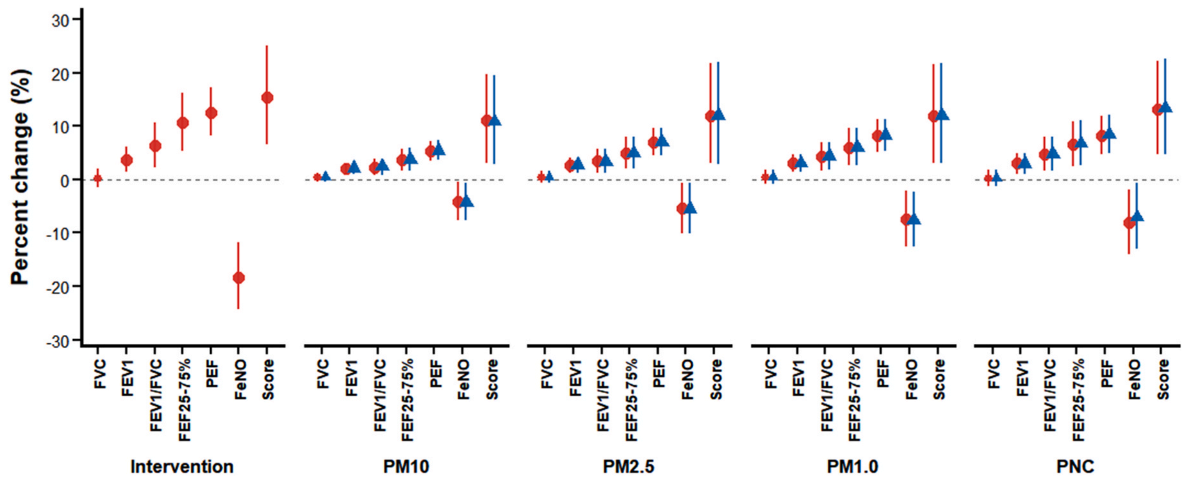

Fig. 3. Percent changes in pulmonary function and attention score following air purifier intervention, and interquartile range decrease in particulate matter. Model1 (red circle): adjusted by sex, age, BMI, history of disease, pet owing, air purifier uses in home, cleaning frequency in home, indirect smoking, and exercise. Model2 (blue triangle): model1 + outdoor PM exposure after school. Interquartile ranges were as follows: PM_{10}, 11.8 μg/m^3; $PM_{2.5}$, 5.7 μg/m^3; $PM_{1.0}$, 2.9 μg/m^3; and total particle number concentration (PNC), 36.8 #/cm^3. Abbreviations: PM_{10}, particulate matter with an aerodynamic diameter ≤10 μm; $PM_{2.5}$, particulate matter with an aerodynamic diameter ≤2.5 μm; $PM_{1.0}$, particulate matter with an aerodynamic diameter ≤1 μm; PNC, particle number concentration; FVC, forced vital capacity; FEV1, forced expiratory volume in 1 s; FEF, forced expiratory flow; PEF, feak expiratory flow; FeNO, fractional exhaled nitric oxide.

changes in airway inflammation (Jia-ying et al., 2021). These discrepancies might be due to factors such as the limited cleaning of filters during longer study periods or transient reductions in FeNO levels influenced by factors such as exercise or diet (Terada et al., 2001; Vints et al., 2005). To evaluate cognitive performance in children, we used the game "Lost in Migration" and observed significant improvements in attention score after air-purifier intervention. Another observational study has explored the relationship between PM exposure and cognitive performance using this platform (Wyatt et al., 2023), and observed that increased PM exposure was generally associated with decreased scores.

In our study, air purifiers were operated for 5–6 h during school hours, approximately a quarter of a 24-h day. We observed significant improvements in health outcomes despite the short duration of the intervention. Similar findings were reported by Zhou et al., who observed cognitive performance improvements after short-term air purifier use of 5–7 h daily over 4 days (Zhou et al., 2023). In line with our findings, a previous study demonstrated health benefits even after adjusting for outdoor PM exposure (Chen et al., 2015). Based on the finding by Park et al. that 32% of children's daily PM2.5 exposure occurred at school, air purifiers are estimated to lower overall daily cumulative $PM_{2.5}$ exposure by approximately 19.7% (Park et al., 2024). Taken together, these studies and our own suggest that short-term interventions lasting 5–6 h over 5 days can significantly improve children's health indicators.

We investigated the impact of varying air purifier CADRs and the number of air purifiers on health outcomes. Effectiveness in reducing indoor PM may depend on higher air flow rate and velocity. However, in our study, the highest PM reduction was with the lower-CADR/MC, followed by the lower-CADR/SC and higher-CADR/MC. Although higher-capacity and multi-unit systems typically provide greater particle removal under controlled test conditions, several real-world factors can attenuate or even reverse this expected relationship. Prior studies show that manufacturer-rated CADR often overestimates effective performance due to noise-related reductions in fan speed, turbulence-induced particle resuspension, airflow short-circuiting between multiple devices, and variability in ultrafine particle removal efficiency (Lowther et al., 2020; Na et al., 2023). In our setting, lower-CADR/MC likely produced more stable airflow with minimal turbulence, enabling greater $PM_{1.0}$ reduction compared to the higher-CADR/MC, which may have generated stronger turbulence, resuspension, or suboptimal airflow interactions. These mechanisms are consistent with previous field studies reporting non-linear and sometimes counterintuitive relationships between CADR specifications and actual indoor PM reduction.

Although the lower-CADR/MC system demonstrated the greatest reduction in PM, the most notable improvement in lung function was observed under the higher-CADR/MC. Significant improvements in pulmonary function were observed across all particle-size fractions, which is broadly consistent with prior evidence showing adverse associations of PM exposure with children's lung function. Notably, the effect appeared stronger with decreasing particle size, which may be biologically plausible because smaller particles penetrate more deeply into the distal airways and alveoli and have greater surface-area–driven oxidative and inflammatory potential (Li et al., 2016; Yang et al., 2020). The observed pattern—where the higher-CADR/MC resulted in the greatest enhancement of lung function despite not producing the largest PM reduction—suggests that pulmonary function may be more sensitive to improvements across particle-size fraction and to the greater ventilation efficiency generated by high-capacity air circulation. These findings highlight the importance of considering particle size–specific pathways and airway mechanics when interpreting the respiratory benefits of portable air cleaner interventions.

Airway inflammation reductions were more pronounced under the lower-CADR/SC across all particle-size fractions. Notably, the lower-CADR/SC showed a significantly greater reduction in airway inflammation than the higher-CADR/MC per IQR decrease in $PM_{1.0}$. Although units with higher CADR are often assumed to provide greater health benefits, our findings—and recent reviews—suggest that the nominal CADR alone does not reliably predict reductions in personal exposure or improvements in airway inflammation (Lu et al., 2024). In real-world indoor environments, effective removal of airborne particles is mediated by a complex interplay of device operation, airflow dynamics, and pollutant characteristics rather than the CADR value alone. First, high-CADR devices typically generate stronger airflow and turbulence, which may increase particle resuspension from surfaces such as floors, desks, or clothing. For example, Kim et al. (2021) observed that stronger circulation enhanced particle re-entrainment, reducing net removal efficiency (M. Y. Kim et al., 2021). Therefore, although the higher-CADR unit might reduce bulk $PM_{2.5}$ and $PM_{1.0}$ mass, the actual reduction in the breathing-zone concentration could be smaller than expected. In contrast, a lower-CADR device operating under slower, steadier airflow may induce less turbulence and maintain more stable removal of particles near the occupant.

Second, reductions in overall $PM_{1.0}$ do not necessarily equate to reductions in the most biologically relevant particle fractions. Ultrafine particles (UFPs; <0.1 μm) and toxic components such as black carbon, transition metals or traffic-derived aerosols play a disproportionately large role in airway inflammation (Schraufnagel, 2020). If the higher-CADR unit was less effective in reducing these reactive fractions—or if its stronger air exchange inadvertently increased infiltration of outdoor pollutants—its impact on airway inflammation could have been attenuated. In contrast, the lower-CADR device may have achieved more meaningful reductions in the high-toxicity fractions or improved breathing-zone exposure despite its smaller nominal capacity.

Third, methodological and design issues may have influenced observed outcomes. Differences in baseline inflammation across periods, limited sample size, or residual sequence or period effects inherent in repeated-measures designs can mask or invert expected dose–response relationships related to device capacity. Indeed, realistic CADR performance in situ is often lower than manufacturer ratings due to room geometry, placement, filter aging and airflow short-circuiting (Al-Rikabi et al., 2025; Küpper et al., 2019). Taken together, these considerations underscore that nominal CADR should not be used as the sole proxy for health-protective performance of air cleaners. Rather, evaluation of airflow behavior, breathing-zone concentrations, pollutant size/-composition, and the study design context are essential when interpreting differential effects on airway inflammation.

Oxidative stress induced by reactive oxygen species (ROS) may be a plausible pathogenic mechanism linking PM exposure to respiratory outcomes. ROS include oxygen radicals, which contain one or more unpaired electrons, as well as non-radical oxidizing agents (Bayr, 2005). PM exposure may stimulate macrophage-driven inflammatory and oxidative responses, leading to increased production of reactive radicals (Vignais, 2002). Excessive ROS may disturb the oxidant–antioxidant balance, causing cellular damage and triggering inflammatory signaling pathways. These may contribute to airway inflammation and altered pulmonary function in children (Barnes, 1990).

Exposure to particulate matter (PM) has been associated with diminished cognitive performance in children. PM can reach the central nervous system (CNS) via two primary pathways: 1) a fraction of PM deposited in the nasal cavity can undergo translocation across the nasal epithelium and ascend along the olfactory nerve pathway to the olfactory bulb; and 2) PM that evades mucociliary clearance or macrophage phagocytosis in the alveoli can translocate into the systemic circulation, subsequently reaching the blood-brain barrier (BBB) and penetrating the brain parenchyma (Kreyling, 2016; Oberdörster et al., 2004). PM can traverse the intact BBB through various mechanisms, including carrier-mediated transport via transporter proteins or receptor-mediated, energy-dependent active transport (Kafa et al., 2015). Protein-mediated transport of PM can trigger the activation of glial cells, contributing to neurotoxicity characterized by neuroinflammation and oxidative stress (Sharma et al., 2009).

In this study, we employed the "Lost in Migration" brain training game to assess selective attention and response inhibition. The prefrontal cortex (PFC) plays an essential role in regulating these cognitive processes (Tanji and Hoshi, 2008). Thus, neuroinflammation in the CNS, particularly within the brain parenchyma, can alter the electrophysiological and synaptic properties of PFC neurons via proinflammatory mediators, leading to excitatory/inhibitory imbalance and disturbed oscillatory synchronization (Estes and McAllister, 2014; Mittli, 2023). This network disruption may contribute to cognitive and behavioral symptoms. Children may have increased susceptibility due to the ongoing development of the PFC (Rauh and Margolis, 2016). It is hypothesized that even short-term PM exposure impairs children's cognitive performance, while air purification may improve it.

Notably, greater percentage improvements in health outcomes were observed following reductions in $PM_{1.0}$. Due to their smaller size, $PM_{1.0}$ particles can penetrate deeper into the lower respiratory tract, penetrate deeply into the alveoli and translocate via the olfactory route (Mistry et al., 2015), and possess a larger surface-to-volume ratio facilitating the carriage of toxic organic gases and transition metals (Schraufnagel, 2020).

Nonetheless, several limitations of this study should also be noted. A 1-week washout period may not have been sufficient to completely eliminate carryover effects for cognitive performance. Because repeated use of the brain-training platform may induce persistent practice-related improvement, some residual bias cannot be excluded. Nevertheless, we adjusted for play number in the model to account for learning effects across repeated assessments, which likely reduced, although did not completely remove, potential bias in the estimated treatment effects. No statistically significant differences in pulmonary function were observed across all CADRs. Given the consistent weekday time–activity patterns of individual participants, unidentified confounding factors influencing pulmonary function may have been non-differentially misclassified in all intervention periods, which lead the bias toward the null. Nevertheless, a lower-CADR air purifier is sufficient to elicit improvement in pulmonary function. Also, insufficient sample size and exposure duration may have obscured the detection of differences in pulmonary function and cognitive performance according to the CADR levels of air purifiers. Further studies should incorporate larger sample sizes and longer-term exposure assessment to better elucidate these associations. In addition, baseline household characteristics such as home air purifier use and household smoking may partly reflect socioeconomic status, which may have introduced residual confounding of the estimated intervention effects. Lastly, we could not account for several potential confounding factors related to early-life development, such as breastfeeding duration, birth weight or gestational age, which may have influenced children's pulmonary function and cognitive performance.

5. Conclusions

This study evaluated classroom-based air purification and found that PM reduction led to significant improvements in children's pulmonary function, airway inflammation, and cognitive performance. This suggests that even short daily interventions can provide health benefits, particularly regarding smaller PM size. While this study offered limited evidence on the specific impact of air purifier CADR and quantity, future research is crucial to determine these optimal specifications through designs that control for factors like room volume and exposure duration, alongside enhanced statistical power.

Ethics approval

This study was approved by the Institutional Review Board of Yonsei University Health System (4-2019-1231). All participants provided informed consent prior to taking part.

CRediT authorship contribution statement

Kyungjun Jeong: Formal analysis, Writing – original draft. **Yongjin Lee:** Formal analysis, Writing – original draft. **Taeyoung Yu:** Formal analysis, Investigation. **Minji Park:** Formal analysis, Investigation. **Daeryong Kang:** Conceptualization, Methodology. **Dongchun Shin:** Conceptualization, Methodology. **Jaelim Cho:** Validation. **Changsoo Kim:** Funding acquisition, Project administration, Supervision, Writing – review & editing.

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.envres.2026.124796.

Data availability

The data that has been used is confidential.

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