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Pilot study of high-performance air filtration for classroom applications

Abstract A study was conducted to investigate the effectiveness of three air purification systems in reducing the exposure of children to air contaminants inside nine classrooms of three Southern California schools. Continuous and integrated measurements were conducted to monitor the indoor and outdoor concentrations of ultrafine particles (UFPs), fine and coarse particulate matter ($PM_{2.5}$ and PM_{10}, respectively), black carbon (BC), and volatile organic compounds. An heating, ventilating, and air conditioning (HVAC)-based high-performance panel filter (HP-PF), a register-based air purifier (RS), and a stand-alone air cleaning system (SA) were tested alone and in different combinations for their ability to remove the monitored pollutants. The combination of a RS and a HP-PF was the most effective solution for lowering the indoor concentrations of BC, UFPs, and $PM_{2.5}$, with study average reductions between 87% and 96%. When using the HP-PF alone, reductions close to 90% were also achieved. In all cases, air quality conditions were improved substantially with respect to the corresponding baseline (preexisting) conditions. Data on the performance of the gas-absorbing media included in the RS and SA unit were inconclusive, and their effectiveness, lifetime, costs, and benefits must be further assessed before conclusions and recommendations can be made.

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Key words: Air filtration; Removal effectiveness; School classrooms; Ultrafine particles; Black carbon; Volatile organic compounds.

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Practical Implications
The installation of effective air filtration devices in classrooms may be an important mitigation measure to help reduce the exposure of school children to indoor pollutants of outdoor origin including ultrafine particles and diesel particulate matter, especially at schools located near highly trafficked freeways, refineries, and other important sources of air toxics.

Introduction

Numerous epidemiological and toxicological studies have found positive associations between exposure to atmospheric particulate matter (PM) and adverse health effects (Environmental Protection Agency Integrated Science Assessments, 2009; Pope and Dockery, 2006). Although air quality standards have been established for outdoor ambient environments, a significant portion of human exposures to PM occurs indoors, where people spend around 85–90% of their time. Hence, it is important to understand and reduce the sources of both indoor and outdoor PM. Indoor PM consists of outdoor particles that have infiltrated indoors, particles emitted indoors (primary), and particles formed indoors (secondary) from precursors emitted both indoors and outdoors.

Because of their immature respiratory systems and greater breathing rates per body weight, children are particularly susceptible to potential health hazards related to PM exposure, which include asthma, lung inflammation, allergies, and other types of respiratory and cardiovascular problems (Liu et al., 2009; Patel and Miller, 2009; Schwartz, 2004). Children in California spend approximately 8% of their time in school (i.e., 4-h/day × 180 day/year), which is second only to the amount of time they spend at home (75%; Wiley et al., 1991). Thus, minimizing the concentration of PM as well as that of other air contaminants (e.g., volatile organic compounds or VOCs) inside classrooms is important, especially at schools located in close proximity to roadways and other substantial sources of air pollution.

The installation of panel filters inside the heating, ventilating, and air conditioning (HVAC) system is a common mitigation measure to reduce the concentration of (and exposure to) indoor air pollutants. Common medium-performance filters with a Minimum Performance Reporting Value (MERV) of 7 (those installed in many U.S. commercial buildings and schools) remove only a small fraction of the particles with aerodynamic diameters (d) lower than 0.3 μm, although higher reductions are generally achieved for larger particles. Diesel PM, which has recently been classified as a human carcinogen by the International Agency for Research on Cancer (IARC; Benbrahim-Tallaa et al., 2012), generally consists of particles <0.3 μm and accounts for more than 80% of the total cancer risk from air toxics in the California South Coast Air Basin (MATES III Study; South Coast Air Quality Management District, 2008). New evidence also suggests that ultrafine particles (UFPs; $d < 0.1$ μm) have harmful health effects beyond those caused by particle mass and may be more toxic than fine particles ($PM_{2.5}$; $d < 2.5$ μm) and coarse PM (PM_{10}; $d < 10$ μm; HEI, 2010; Li et al., 2003; Renwick et al., 2004).

Filtration in classrooms presents some unique challenges. The older HVAC systems that exist in older schools were not designed with air filtration in mind. The classroom is a noise-sensitive environment, so filtration systems must meet strict decibel limits when in operation. Classrooms often have high ventilation rates with doors and windows that are frequently open to outside air. Finally, classrooms are large, densely occupied spaces with much activity that can lead to indoor generation of particles and other pollutants.

The main objective of this study was to investigate the effectiveness of three different air purification systems based on particle filtration and/or sorption of gaseous pollutants in reducing the exposure of children to outdoor-infiltrated air contaminants inside nine classrooms at three Southern California schools. To this end, the South Coast Air Quality Management District (SCAQMD, Diamond Bar, CA, USA) worked in close collaboration with IQAir (IQAir North America, La Mirada, CA, USA), a company that specializes in air purification solutions and with Thermal Comfort Systems (Thermal Comfort Systems Inc., Northridge, CA, USA), an HVAC contractor. Of particular interest was the removal of various sizes and types of PM, especially the smaller fractions associated with diesel engine exhaust. Solutions for removing gaseous air contaminants that may be air toxics or cause odors were also examined.

The installed systems were tested for their ability to remove UFPs, $PM_{2.5}$, PM_{10}, black carbon (BC), and VOCs from the selected classrooms. UFPs are primarily produced from the combustion of fossil fuels, but indoor activities such as cooking, cleaning, painting, gluing, and drawing can also lead to substantial increases in the concentration of UFPs (Afshari, 2005; Gehin et al., 2008; Morawska et al., 2009). Fine PM is mainly emitted from motor vehicles, power plants, residential wood burning, forest fires, agricultural burning, and other combustion activities, and it has well-established health effects. Sources of PM_{10} include crushing or grinding operations, resuspension of dust from vehicles traveling on roads, and other mechanical processes. Sometimes referred to as soot, BC is related closely to elemental carbon and is a component of PM that is formed through the incomplete combustion of fossil fuels and biomass. Most of the atmospheric BC is in the fine or ultrafine particle size ranges, and the majority of BC in Southern California comes from diesel PM emissions. VOCs are comprised of gases that are emitted by a variety of evaporative processes and combustion sources, including paints, cleaning supplies, pesticides, building materials, household products, refineries, and mobile sources. Concentrations of many VOCs may be much higher indoors than outdoors (Bruno et al., 2008; Jia et al., 2007). Exposure to many of these organic contaminants has also been associated with a wide array of toxic health effects.

While several previous studies have measured indoor $PM_{2.5}$ and PM_{10} concentrations in schools, there have been only a few reports of UFP levels in classrooms, among which only three were for works conducted in the United States (Mullen et al., 2011; Parker et al., 2008; Zhang and Zhu, 2012). However, in most cases, the effect of mechanical ventilation and air filtration performance on the measured indoor particle levels was not discussed. To the best of our knowledge, this is the first study to provide data on the effectiveness of different air filtration solutions in reducing PM, UFP, BC, and VOC concentrations in actual occupied classroom settings.

Methods

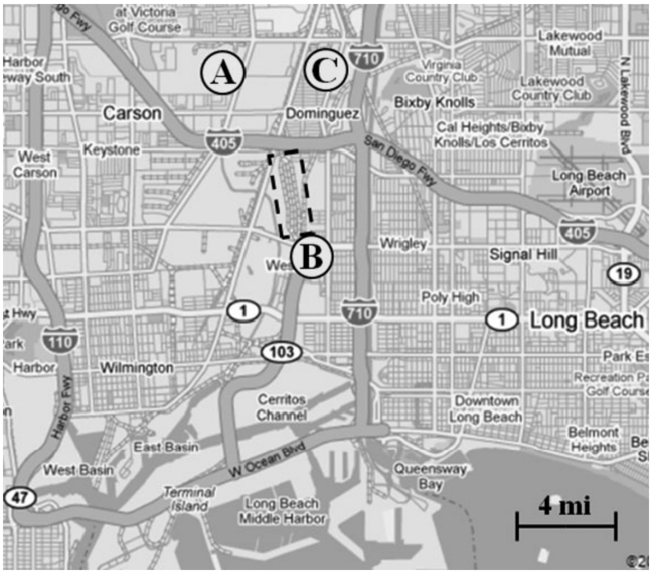

Fig. 1 Map of the study area. The circles indicate the locations of the three elementary schools participating in this study: Del Amo (A), Hudson (B), and Dominguez (C). The Union Pacific Railroad Intermodal Container Transfer Facility is marked by the black rectangle

these important pollution sources has lead to local concerns about the air quality in the surrounding communities.

At each of the three elementary schools, three classrooms with similar structural characteristics and ventilation conditions were selected to provide reproducible test conditions for the various air purification systems deployed. All classrooms (varying between 210 and 260 m^3 in size) already included forced-air HVAC systems. The main characteristics of all nine classrooms are listed in Table 1.

Prior to beginning this study, none of the selected classrooms featured any specific air purification device other than one or more medium-performance panel filters [minimum efficiency reporting value (MERV) 7] installed inside the respective HVAC systems. The typical replacement interval for these air filters is approximately 3 months according to schools' schedules. The primary purpose of this panel filter (PF) is to remove coarse particles and dust to protect the HVAC system's heating and cooling coils. These filters generally provide little or no removal of smaller particles or gaseous pollutants.

Air purification solutions

Three different air purification solutions were tested for their ability to remove UFPs, $PM_{2.5}$, PM_{10}, BC and, where possible, VOCs from the air stream: an HVAC-based high-performance panel filter (HP-PF), a register-based air purifier (or register system; RS), and a stand-alone system (SA). All systems were provided, installed, and maintained by IQAir.

The HP-PFs used for this study utilize a multilayered, non-woven filtration media, made of glass and synthetic fibers. The media are arranged in a 'mini-pleat' configuration, similar to that of HEPA filters used in clean-room applications. Compared to most standard/conventional medium-performance MERV filters, the HP-PFs used for this study (rated MERV 16) are twice as thick (5.08 cm in depth) and have a much larger filter surface area (5–9 times larger). Due to the increased surface area, they generally have similar air resistance properties as conventional filters and thus do not act to reduce the airflow through the HVAC system. The airflow data obtained before and after the HP-PF installation confirm this claim (see Table S2). The pressure drop of the HP-PF as specified by the manufacturer is 95 Pa at 2.5 m/s face velocity.

A RS device is installed directly on or replaces the HVAC register, where the air supply enters the room. The RS units used for this study were custom fabricated to match the size of the supply vents in each classroom and equipped with a high-performance particle filter (MERV 16) for the removal of PM and between 4 and 9 high-capacity gas-phase filter cartridges to help reduce certain gaseous pollutants from the air stream (e.g., VOCs). This particular design allows for a longer contact time between the filtration media and the gaseous pollutants than would be permitted using an activated carbon panel filter in the HVAC system. Nevertheless, the RS does not seem to reduce the overall HVAC system airflow according to our testing results (see Table S2). The gas-phase cartridges used in each RS consisted of a mixture of granular activated carbon and $KMnO_4$-impregnated alumina pellets. Different amounts of this mixture were used (i.e., 10–22.5 kg per RS) depending on the size of the RS.

Similarly to activated carbon filters tested in previous studies (e.g., Alvarez et al., 2008), the gas-phase filter cartridges used in this RS system may also have the ability to remove ozone (O_3). However, little information exists regarding the potential for this type of media to remove O_3 and the effect of VOC loadings on O_3 removal (Bekö et al., 2009; Metts and Batterman, 2006).

A SA unit is a self-contained air cleaning device that operates independently of a classroom's HVAC. The system used for this study is 1.95 m tall and has a footprint of about 0.41 m^2. The SA is tamper-proof, runs on a standard power circuit, and is built with an energy efficient fan, located inside a specially designed inner housing for quiet operation. Indoor air enters from the lower part of the system (about 15 cm off the ground) and passes, sequentially, through a high-performance particle filter (MERV 16) for the removal of PM, 12 high-capacity gas-phase filter cartridges (the total media weight was 46 kg and the contact time 0.21 s) for the removal

Table 1 Structural characteristics and ventilation conditions of the nine classrooms selected for this study

	Del Amo			Hudson			Dominguez		
Classroom ID	DA-6	DA-7	DA-8	H-11	H-15	H-52	DZ-7	DZ-9	DZ-11
Occupants (*n*)	18	19	22	21	11	17	28	28	29
Room size (m)	11.6 × 7.3 × 3.0	11.6 × 7.3 × 3.0	11.6 × 7.3 × 3.0	9.1 × 9.1 × 2.7	9.1 × 9.1 × 2.7	9.4 × 8.2 × 2.7	11.6 × 6.7 × 3.4	11.6 × 6.7 × 3.4	11.6 × 6.7 × 3.4
HVAC type	DW-M	DW-M	DW-M	DM-ZR	DM-ZR	DR	DR	DR	DR
HVAC operation	Manual	Manual	Manual	Automatic	Automatic	Automatic	Manual	Manual	Manual
Supplied airflow[a] (m^3/h)	2039	2039	2124	1427	1534	2100	2790	2856	3011
Return airflow[a] (m^3/h)	1546	850	1223	1359	1461	1665	2200	1623	2234
Mechanical ventilation[a] (m^3/h)	493	1189	901	68	73	435	590	1233	777
Filtration rate[b] (per hour)	8.0	8.0	8.4	6.4	6.9	10.1	10.6	10.8	11.4
Filter type	Pleated	Pleated	Pleated	Pleated	Pleated	Fiberglass	Pleated	Pleated	Pleated
Filter thickness (cm)	5.08 (2″)	5.08 (2″)	5.08 (2″)	5.08 (2″)	5.08 (2″)	5.08 (2″)	2.54 (1″)	2.54 (1″)	2.54 (1″)
Filter rating	MERV 7	MERV 7	MERV 7	MERV 7	MERV 7	Unclassified	MERV 7	MERV 7	MERV 7
Supply vents (*n*)	1 (wall)	1 (wall)	1 (wall)	1 (ceiling)	1 (ceiling)	4 (ceiling)	3 (ceiling)	3 (ceiling)	3 (ceiling)
Return grille (*n*)	1 (wall)	1 (wall)	1 (wall)	1 (ceiling)	1 (ceiling)	1 (ceiling)	1 (ceiling)	1 (ceiling)	1 (ceiling)

DW-M, ducted wall-mount; DM-ZR, ducted multizone rooftop; DR, ducted rooftop; HVAC, heating, ventilating, and air conditioning; MERV, minimum efficiency reporting value.
A balometer was used for all airflow measurements.
[a]With existing panel filter.
[b]Supplied airflow/room volume.

of VOCs and other gaseous pollutants commonly found indoors, and a final high-performance particle post-filter. When operated at 1362 m^3/h (as during this study), this SA unit has a power draw of 157 W and complies with the stringent noise requirements for new in-classroom equipment adopted by many schools [45 db(A) noise threshold].

In-classroom configurations

Different combinations of the HVAC-based HP-PF, RS air purifier, and SA system were used inside the studied classrooms to evaluate their performance under occupied conditions. Specifically, the following configurations were used: (1) HP-PF alone; (2) RS alone, although in some cases it was operated in combination with the conventional/medium-performance PF (MERV 7) already installed inside the HVAC prior to the beginning of the study (RS + PF); (3) RS in conjunction with a HP-PF (RS + HP-PF); (4) SA system in classrooms with no HVAC running; (5) SA system in classrooms with an HVAC running, in which case a conventional/medium-performance PF (MERV 7) was already installed inside the HVAC (SA + PF); (6) SA system in conjunction with a HP-PF (SA + HP-PF). A schematic representation of these six configurations is shown in Figure 2.

Indoor and outdoor measurements

Four mobile air quality monitoring stations were used to measure the indoor and outdoor concentrations of the targeted air pollutants. Each of these stations was comprised of a mobile cart supporting the following instruments: (i) a *portable aethalometer* (model AE42; Magee Scientific, CA, USA) for the continuous measurements (i.e., 5-min time resolution) of BC concentrations (ng/m^3); (ii) a *water-based condensation particle counter* (CPC model 3781; TSI, MN, USA) for the continuous measurements (i.e., 1-min time resolution) of the particle number concentration (n/cm^3), an indicator of UFPs; (iii) a *laser particle counter* (IQAir ParticleScan Pro) for determining the number concentration (n/cm^3) of particles between 0.3 and 2.5 μm in diameter [$PM_{(0.3–2.5)}$] at 1-min time resolution; (iv) a *laser-based particle mass monitor* (Aerocet 531 Aerosol Particulate Profiler; MetOne, OR, USA) for the continuous measurements (i.e., 3-min time resolution) of the mass concentration ($\mu g/m^3$) of both $PM_{2.5}$ and PM_{10}; and (v)

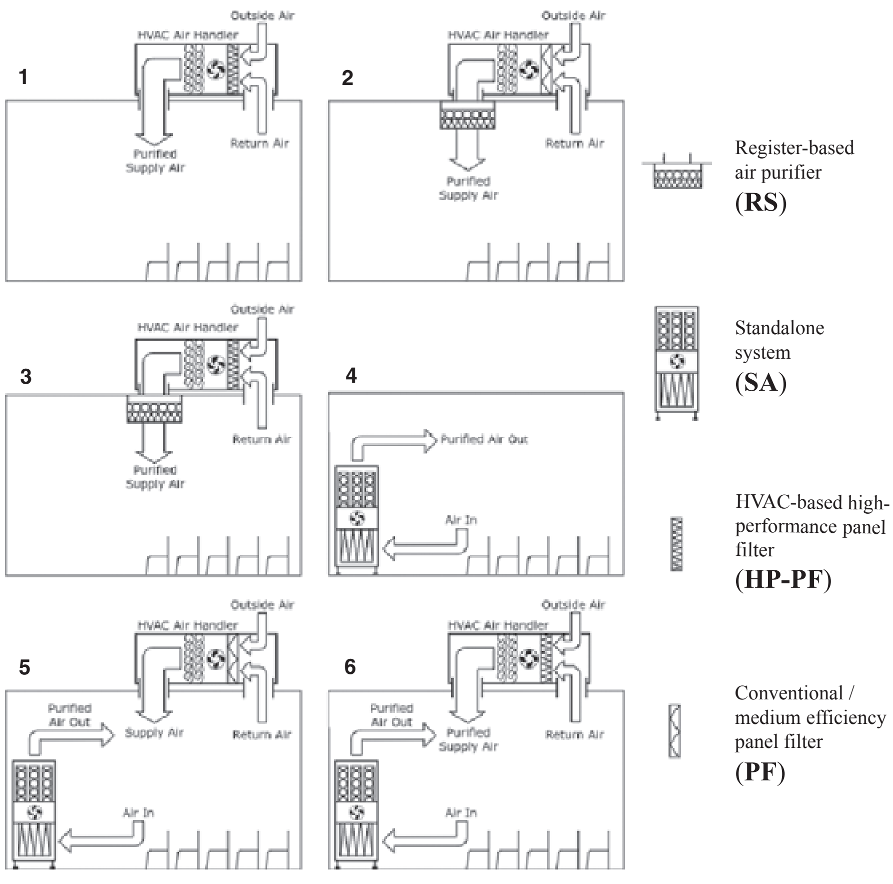

Fig. 2 Schematic representation of the six air purification solutions tested in this study. Different combinations of the heating, ventilating, and air conditioning (HVAC)-based high-performance panel filter (HP-PF), register-based air purifier (RS) air purifier, and standalone system (SA) system were used inside the studied classrooms to evaluate their performance

6-liter SUMMA® canisters to collect time-integrated air samples over the course of a typical school day (i.e., 6-h). Samples were then analyzed by Gas Chromatography-Mass Spectrometry (GC-MS) to measure the concentrations of 61 specific VOCs (ppbv) using the TO-15 method developed by the Environmental Protection Agency (1999).

At each school, one air quality monitoring cart was set up outside to sample outdoor air. The remaining three stations were placed indoors, one in each classroom, near one of the walls and just a few meters away from the students. Measurements were made away from all air conditioning vents to better represent mixed Indoor Air Quality conditions as experienced by students and teachers. All sensors and inlets were approximately 90 cm above the floor or about the height of a child's head when seated. The performance of each of the tested air purification solutions was then evaluated by comparing the indoor concentrations of the targeted air pollutants to the corresponding outdoor levels. Baseline measurements were taken before installing any of the air purification solutions to estimate the preexisting removal effectiveness of the classrooms before modification. Measurements that were found to be inaccurate or unrepresentative due to meteorological conditions (e.g., rain), improper cart placement, or instrument malfunction were not considered in the data analysis.

Before and after school hours, the four measurement stations were collocated in a storage room and the continuous instruments were run 'side-by-side' to provide quality assurance of the collected data, to estimate the precision characteristics, and to identify any potential problems. The accuracy of the colocated measurements from the four sets of instruments used during this study was always within 5%. Instruments that failed were identified for immediate repair, and their data for that monitoring period removed from the analysis. Table 2 illustrates the specific air purification solutions that were tested inside each of the nine classrooms, along with the dates when all baseline and actual measurements were taken. The three schools were tested one at a time from April to December 2008 for a total of over 150 valid measurement days across all schools and classrooms. The number of measurement days at each school is shown in Table 4. The period of sampling was during regularly scheduled school hours (from 09:00 to 15:00), with minor adjustments for school schedule changes, and in actual occupied classroom settings.

A balometer was used to measure the airflow at both the supply vent and the return register before and after the installation of the RS and/or HP-PF. The mechanical ventilation rate for each classroom was calculated as the difference between the supply and return airflows (Table 1).

Table 2 Summary of the air purification solutions tested in each of the nine classrooms. The dates when all baseline and actual measurements were taken are also included

	Configuration used			
School/Class ID	04/07–11/08	04/14–18/08	04/21–25/08	04/28/08–05/02/08
Del Amo/DA-6	Baseline	SA + PF	SA + PF	SA + HP-PF
Del Amo/DA-7	Baseline	RS	RS	RS
Del Amo/DA-8	Baseline	HP-PF	HP-PF	HP-PF
	05/12–16/08	05/19–23/08	05/26–30/08	06/02–06/08
Hudson/H-11	Baseline	HP-PF	RS + HP-PF	RS + HP-PF
Hudson/H-15	Baseline	HP-PF	RS + HP-PF	RS + HP-PF
Hudson/H-52	Baseline	HP-PF	RS + HP-PF	RS + HP-PF
	11/18–26/08	12/01–05/08	12/08–12/08	12/15–19/08
Dominguez/DZ-7	Baseline	SA/SA + PF	SA + HP-PF	SA + HP-PF
Dominguez/DZ-9	Baseline	HP-PF	HP-PF	HP-PF
Dominguez/DZ-11	Baseline	HP-PF	RS + HP-PF	RS + HP-PF

HP-PF, HVAC-based high-performance panel filter; HVAC, heating, ventilating, and air conditioning; RS, register-based air purifier; SA, stand-alone system; PF, conventional/medium efficiency panel filter.

Results and discussion

Removal of PM and other particle species

Study average outdoor BC, UFP, $PM_{2.5}$, and PM_{10} levels at all schools were similar to those seen throughout the South Coast Air Basin (SCAB) during previous monitoring campaigns conducted by SCAQMD and represent typical outdoor conditions for most urban areas of SCAB (Table 3). Differences in measured outdoor concentrations among the three school sites are mainly due to different proximity to local emission sources and temporal variability. Daily and weekly average indoor and outdoor concentrations of the measured pollutants at all schools and classrooms are provided in Table S1, along with the corresponding average indoor/outdoor ratios.

Figure 3 and Table 4a summarize the study average particle removal effectiveness (or removal performance, here defined as the percentage reduction in the indoor concentration of a particular pollutant relative to its concurrent outdoor concentration) achieved by the six air purification solutions. Indoor and outdoor mass and particle number concentrations were averaged over the duration of a typical school day and across all days, classrooms, and schools. The corresponding average particle removal effectiveness values for each elementary school are reported in Tables 4b (Del Amo), 4c (Hudson), and 4d (Dominguez).

Overall, the RS + HP-PF combination was the most effective solution for reducing the indoor concentrations of BC, UFPs, $PM_{2.5}$ mass, and $PM_{(0.3–2.5)}$ count, with average removal effectiveness varying from 87% to 96% (Figure 3 and Table 4a). When using the HP-PF alone, the study average removal performance for

Table 3 Summary statistics for the outdoor BC, UFPs, $PM_{(0.3–2.5)}$ count, $PM_{2.5}$ mass, and PM_{10} concentrations measured at all schools

	BC ($\mu g/m^3$)	UFP (n/cm^3)	$PM_{(0.3–2.5)}$ count (n/cm^3)	$PM_{2.5}$ mass ($\mu g/m^3$)	PM_{10} mass ($\mu g/m^3$)
Del Amo					
Average	2.24	40 354	56	10.9	39.6
Median	1.69	38 854	53	10.8	41.1
s.d.	1.22	9920	22	3.25	10.8
Min	0.95	19 124	21	5.61	5.61
Max	4.45	57 526	117	17.9	55.5
Hudson					
Average	1.53	38 174	42	11.9	51.8
Median	1.14	38 368	41	12.7	48.8
s.d.	0.86	15 434	19	6.73	23.4
Min	0.73	14 643	13	2.34	18.7
Max	3.76	80 163	74	29.0	99.0
Dominguez					
Average	5.43	28 922	193	12.7	44.4
Median	4.67	29 061	221	11.0	46.7
s.d.	2.72	8566	122	9.72	20.7
Min	1.98	16 048	15	1.29	7.99
Max	11.2	42 651	364	35.3	86.1

BC, black carbon; PM, particulate matter; UFP, ultrafine particles.

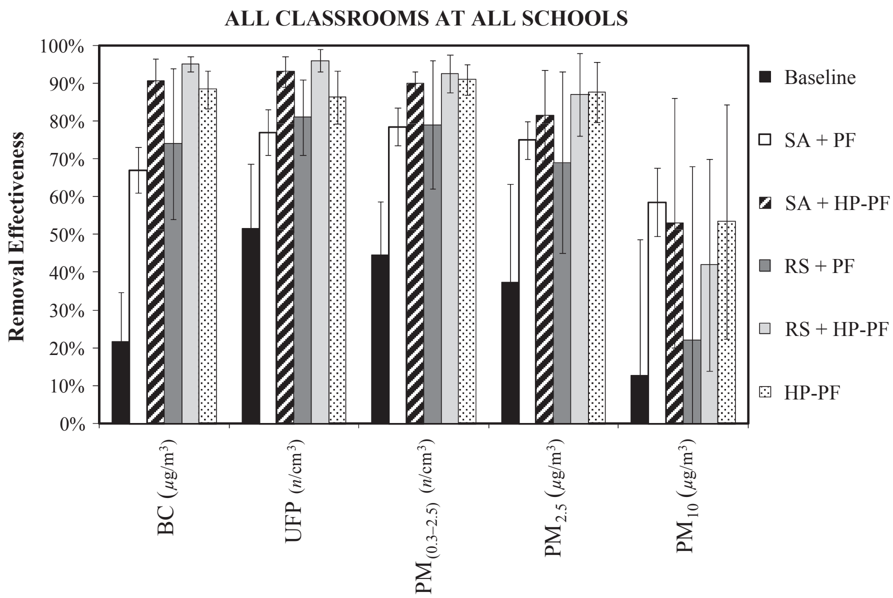

Fig. 3 Particle removal effectiveness values (%) achieved by the six air purification solutions. Bars indicate data averaged at all schools and in all classrooms. Vertical lines represent standard deviations for each bar

the targeted pollutants was also close to 90% (88%, 86%, 91%, and 88%, for BC, UFPs, $PM_{(0.3–2.5)}$ count, and $PM_{2.5}$ mass, respectively).

The SA system is well suited for indoor environments not equipped with an HVAC. To simulate conditions similar to those encountered in older classrooms not equipped with a forced-air climate control device, the HVAC in room DZ-7 (at Dominguez) was intentionally turned off for part of the study. When the SA unit was running with the HVAC off, the removal effectiveness was close to 90% for BC, UFPs, and $PM_{(0.3–2.5)}$ count (Table 4d). For BC and UFPs, these percentages were slightly lower when the HVAC was running because more of the smaller particles (mostly unfiltered by the existing conventional PF) were entering the classrooms from outdoors. It should be noted that the performance of a SA system is likely to be affected by the proximity of the device to doors, windows and air supply registers, the lower airflow rate 'processed' by the SA unit relative to the flow rate handled by the HVAC system (i.e., lower Clean Air Delivery Rate; Zhang et al., 2011), and other factors intrinsic to the particular classroom setup considered.

In all cases, air quality conditions were improved substantially with respect to the corresponding baseline measurements, when removal effectiveness values for

Table 4 Particle removal effectiveness values (%) achieved by the six air purification solutions tested in this study. Data represent averages (a) at all schools and in all classrooms, (b) at Del Amo, (c) at Hudson, and (d) at Dominguez

	Study days (*n*)	BC (%)	UFP (%)	$PM_{(0.3–2.5)}$ count (%)	$PM_{2.5}$ mass (%)	PM_{10} mass (%)
(a) All classrooms and all schools						
Baseline	48	22 ± 13	52 ± 17	45 ± 14	37 ± 26	13 ± 36
SA + PF[a]	14	67 ± 6	77 ± 6	79 ± 5	75 ± 5	59 ± 9
SA + HP-PF	11	91 ± 6	93 ± 4	90 ± 3	82 ± 12	53 ± 33
RS + PF	15	74 ± 20	81 ± 10	79 ± 17	69 ± 24	22 ± 46
RS + HP-PF	35	95 ± 2	96 ± 3	93 ± 5	87 ± 11	42 ± 28
HP-PF	35	88 ± 5	86 ± 7	91 ± 4	88 ± 8	53 ± 31
(b) Del Amo elementary school						
Baseline	15	8 ± 9	45 ± 16	18 ± 20	27 ± 17	26 ± 26
SA + PF[a]	10	52 ± 7	68 ± 6	60 ± 7	64 ± 5	51 ± 9
SA + HP-PF	5	90 ± 5	92 ± 3	93 ± 1	91 ± 4	74 ± 11
RS + PF	15	74 ± 20	81 ± 10	79 ± 17	69 ± 24	22 ± 46
HP-PF	15	88 ± 4	87 ± 4	89 ± 5	89 ± 5	62 ± 13
(c) Hudson elementary school						
Baseline	15	33 ± 9	56 ± 18	46 ± 11	74 ± 5	54 ± 23
RS + HP-PF	27	96 ± 2	98 ± 2	94 ± 4	94 ± 5	51 ± 30
HP-PF	15	92 ± 2	91 ± 4	93 ± 2	93 ± 4	59 ± 33
(d) Dominguez elementary school						
Baseline	18	24 ± 21	54 ± 16	70 ± 11	11 ± 55	−42 ± 60
SA[b]	3	90 ± 4	94 ± 2	92 ± 6	75 ± 10	31 ± 42
SA + PF[a]	4	82 ± 5	86 ± 5	97 ± 2	86 ± 4	66 ± 8
SA + HP-PF	6	91 ± 6	94 ± 4	87 ± 5	72 ± 20	32 ± 55
RS + HP-PF	8	94 ± 2	94 ± 3	91 ± 6	80 ± 17	33 ± 25
HP-PF	18	85 ± 8	81 ± 13	91 ± 5	81 ± 16	39 ± 48

BC, black carbon; HP-PF, HVAC-based high-performance panel filter; HVAC, heating, ventilating, and air conditioning; PM, particulate matter; RS, register-based air purifier; SA, stand-alone system; MERV, minimum efficiency reporting value; UFP, ultrafine particles.

[a]Operated in conjunction with a standard (MERV 7) panel filter installed in the HVAC system.

[b]The HVAC system was turned off.

the different pollutants were typically between 20% and 50% (Table 4a). The intraclassroom variability of the measured removal effectiveness data was low, as indicated by the low standard deviations given in Table 4a. This reflects the fact that all air purification solutions were characterized by high performance at all schools and in all classrooms.

The negative removal effectiveness for PM_{10} associated with average baseline conditions at Dominguez (see Table 4d) indicates that, at times, indoor concentrations were higher than the corresponding outdoor levels. This is likely due to resuspension of dust and other relatively large particles caused by in-classroom activities such as walking and cleaning (Branis et al., 2005; Parker et al., 2008). Due to the presence of these indoor sources, the removal performance of PM_{10} was lower than that of other particle measurements. Typically, the removal effectiveness for PM_{10} approached 100% right before the school day started and during lunchtime (when students and staff members were outside the classroom and the HVAC was running) and was substantially lower when classes were in session. The effect of indoor activities on PM_{10} levels inside classroom H-15 (Hudson elementary) on May 21, 2008 is illustrated in Figure 4.

Activities occurring immediately outside the school boundaries also influenced the indoor concentrations of

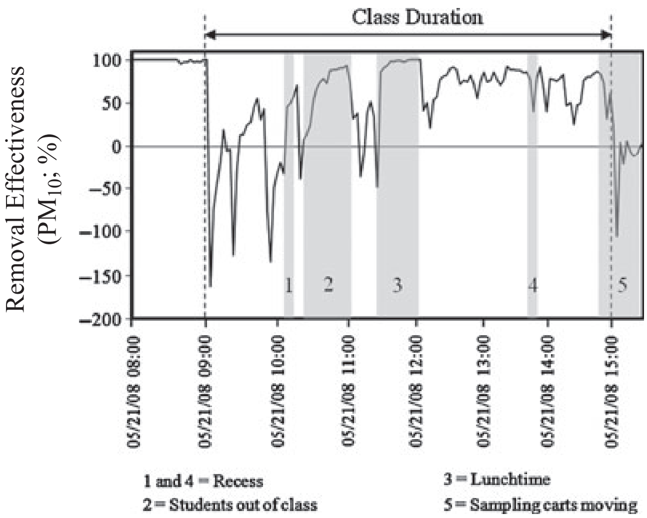

Fig. 4 Effect of indoor activities on the removal performance of PM_{10} at Hudson elementary school (room H-15) on May 21, 2008. PM, particulate matter

some pollutants and thus their corresponding removal performance values. Figure 5 shows the effect of increased motor vehicle emissions due to the morning drop-off of students (starting at approximately 07:30 AM) on the outdoor concentrations of BC and the associated spikes in indoor BC levels occurring just before the beginning of the school day, when the

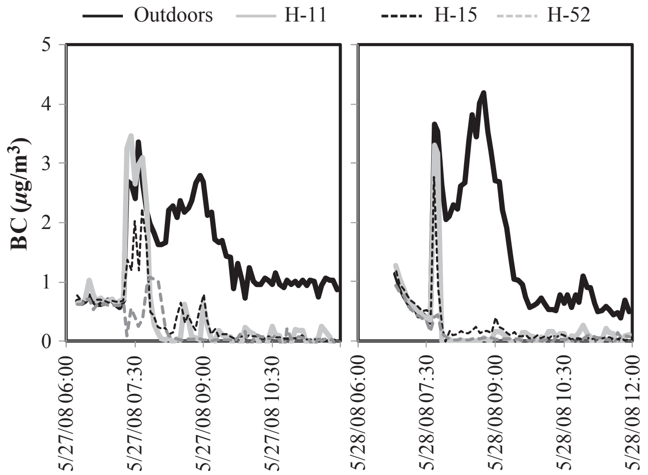

Fig. 5 Effect of before school activities on black carbon (BC) concentrations. Early morning (preschool) peaks at Hudson elementary school show an increase in both indoor (rooms H-11, H-15, and H-52) and outdoor levels due to morning drop-off traffic

classroom doors were left open. Overall, these indoor peaks caused a relatively small decrease in the calculated removal performance when averaged over the course of the entire school day. Similar results were also observed for UFPs and $PM_{(0.3–2.5)}$ and are consistent with data collected in other classroom environments (Guo et al., 2010), where human activities such as cigarette smoking and the operation of mower near the school sites have also been related to sudden increases in the outdoor and indoor levels of these pollutants.

As discussed earlier, the HP-PFs used for this study are deeper than most standard/conventional medium-performance MERV filters. However, due to their increased surface area and proprietary design, they generally have similar air resistance properties as conventional PF and thus do not reduce the airflow through the HVAC system. Replacing a conventional PF (typically 2.54 cm in depth) with a deeper HP-PF (5.08 cm deep) did not alter the measured airflow in any of the studied classrooms substantially (see Table S2 for details). Adding a RS without upgrading to a HP-PF reduced the HVAC system airflow by an average of 9%. This small reduction is due to the increased pressure drop resulting from the addition of a gas-phase filtration media. Using a RS while also upgrading to a HP-PF (RS + HP-PF configuration) altered the airflow by only 1–3%. At Hudson elementary school, installation of the RS in classrooms H-11 and H-15 required a widening of the connection to the supply duct. This caused an airflow increase between 17% and 24% with RS. Data showing the effect of the HP-PF and/or RS on the HVAC system airflow at all schools and in all classrooms can be found in Table S2.

Removal of VOCs

Although canister samples were collected at all schools and classrooms and all samples were analyzed for VOCs, the data recovery at Del Amo and Hudson was insufficient to guarantee an adequate interpretation of the results. The detection limits of the analysis method used at those schools were not low enough to quantify most of the VOCs of interest. After the analysis methods were modified to correct for this problem, reliable VOC data were obtained for Dominguez elementary. Therefore, only VOC data from Dominguez are discussed in this section. Table 5 summarizes the removal effectiveness for: total VOCs [expressed as the sum of 61 individual compounds and 53 unspeciated (unidentified) organic compounds], ethanol (a chemical emitted from both indoor and outdoor evaporative sources), and benzene (a species mostly emitted from gasoline-powered vehicles and often used as an indicator of VOCs of outdoor origin). Large standard deviations reflect the wide concentration ranges for the different chemicals. As expected, existing PF and HP-PFs had virtually no effect on the VOC levels measured indoors, because these air filtration media did not include gas removal capabilities. The SA system demonstrated a 52–73% removal performance for benzene. Daily average concentrations of individual VOCs measured at Dominguez elementary school (i.e., DZ-7, DZ-9, and DZ-11) are given in Table S3.

At all three schools, the indoor concentrations of ethanol were consistently the highest among all measured VOCs and higher than outdoor levels. This organic compound is a common solvent used in white-board markers, detergents, and other cleaning products and has several potential indoor sources. The negative removal effectiveness values shown in Table 5 indicate that the indoor concentrations of some VOCs were often higher than the corresponding outdoor levels. Our findings are in line with those from previous research studies (Bruno et al., 2008; Jia et al., 2007)

Table 5 Average removal effectiveness for total volatile organic compounds (VOCs), ethanol, and benzene at Dominguez

	Dominguez			
	Study days (*n*)	Total VOCs (%)[a]	Ethanol (%)	Benzene (%)
Baseline	18	−114 ± 731	−1230 ± 982	−11 ± 22
SA (HVAC off)[b]	3	15 ± 132	−349 ± 276	52 ± 35
SA + PF (HVAC on)[c]	4	19 ± 198	−587 ± 903	58 ± 33
SA + HP-PF	6	−6 ± 280	−929 ± 853	73 ± 11
RS + HP-PF	8	−3 ± 345	−534 ± 502	58 ± 49
HP-PF	18	−64 ± 404	−1111 ± 1164	1 ± 38

HP-PF, HVAC-based high-performance panel filter; HVAC, heating, ventilating, and air conditioning; RS, register-based air purifier; SA, stand-alone system; VOCs, volatile organic compounds.
[a]Sum of 61 known VOCs and 53 unspeciated organic compounds.
[b]Operated with the HVAC system turned off.
[c]Operated with the HVAC system turned on.

and confirm that several measured indoor VOCs are mostly of indoor origin. Overall, these solutions demonstrated some ability to reduce VOCs indoors, although not as consistently or effectively as the particle filtration. This may be due to the presence of one or more indoor sources of gaseous pollutants. It should be noted that the removal performance of gas-absorbing media (as opposed to filtration substrates) is dependent on media history and may be subject to saturation after experiencing high short-term concentrations or after longer-term use. Also, the organic compounds captured by the gas-phase filter cartridges (as well as those associated with the particles removed on the filter surface) may then undergo chemical transformation and/or desorb into the airstream, further degrading air quality downstream of the air cleaning device (Bekö et al., 2006, 2008; Weschler, 2004). Relative humidity has also been shown to impact the ability of activated carbon filters to remove VOCs. The extent of such impact varies depending on the VOC type (i.e., hydrophobic or hydrophilic) and concentration and the type of activated carbon used (Haghighat et al., 2008; Qi et al., 2006).

As observed by Zhang et al. (2011) in a recent literature review paper on fan-driven air cleaning technologies, sorption is an efficient technology for removing specific gaseous pollutants such as certain VOCs, formaldehyde, O_3, NO_2, SO_2, and H_2S from the indoor air. However, the removal effect for multiple indoor compounds remains unknown, and for a target pollutant, the criteria for selecting the best sorption material to optimize removal over a given time period are generally not available (Zhang et al., 2011). The lifetime, cost, benefits, and maintenance of the gas removal media used in this study must be further assessed before conclusions and recommendations can be made.

Conclusions

An HVAC-based high-performance panel filter (HP-PF; rated MERV 16), a register-based air purifier (RS), and a stand-alone system (SA) were tested alone and in different combinations for their ability to remove particle and gaseous pollutants from classroom environments. When used alone, the study average HP-PF removal effectiveness for BC, UFPs, and $PM_{2.5}$ mass was 86–88%. The removal performance was even higher (i.e., 87–96%) when the same HP-PF was coupled with a RS. Removal effectiveness values for BC and UFPs close to 90% were also measured for the SA system, both when this was used in conjunction with a HP-PF and when the HVAC was turned off. Data on the ability of these technologies to remove VOCs were inconclusive.

Although most of the legislative efforts should focus on ambient PM reduction policies, the installation of highly effective air filtration devices in schools may be an important mitigation measure to minimize exposure of children to indoor pollutants of outdoor origin, especially at schools located near heavily trafficked freeways, refineries, and other important sources of air toxics. Future research should focus on (i) identifying additional technologies for the removal of indoor air pollutants (VOCs in particular), (ii) quantifying the short- and long-term impact of installing highly effective air filtration devices in schools on children's health, productivity, and absenteeism, and (iii) the cost benefits resulting from improved Indoor Air Quality conditions and from a reduction in student exposure to outdoor-infiltrated particles and organic pollutants.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table S1 Daily and weekly average indoor and outdoor concentrations of BC, UFP, $PM_{(0.3–2.5)}$ count, $PM_{2.5}$ mass, and PM_{10} mass at all schools and classrooms.

Table S2 Effect of a high-performance panel filter (HP-PF) and/or a register system (RS) on the HVAC supplied airflow.

Table S3 Daily average concentrations of individual VOCs measured outside Dominguez elementary school and inside three of its classrooms (here referred to as DZ-7, DZ-9, and DZ-11).

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