Effectiveness of Particle Air Purifiers in Improving the Air Quality in Classrooms in Three Urban Public Schools in the Northeastern United States

Effectiveness of Particle Air Purifiers in Improving the Air Quality in Classrooms in Three Urban Public Schools in the Northeastern United States

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Abstract

This study investigates whether Particle Air Purifiers (PAPs) are effective in improving indoor air quality (IAQ) in an urban school setting by removing $PM_{2.5}$ and its elemental constituents from classroom air. In addition, the study examines whether seasonal differences in removal efficiency (RE) exist.

Background: $PM_{2.5}$ found in indoor environments has both indoor and outdoor sources. The fraction of outdoor $PM_{2.5}$ found indoors is related to local outdoor air pollution levels and the condition, age and construction features of a building that increase air exchange. Urban schools that are near major roadways would be expected to have a higher fraction of $PM_{2.5}$ in classroom air originating from outdoor sources. The American child spends most of his or her time indoors therefore, IAQ is very important since exposure to $PM_{2.5}$ is associated with asthma and other respiratory illnesses. As well as home IAQ, Classroom IAQ is important since a child spends a significant portion of time in the school environment.

Methods: Three schools (A, B, and C) in an urban school district in the northeastern United States participated in this study. There were 21 study classrooms. 11 classrooms had an active PAP with a filter and 10 classrooms had a sham PAP with no filter. Background measurements of air were taken in all classrooms prior to sham or filter cleaner placement. Two measuring periods followed background measurement. These measuring periods were Trial 1 (during winter months) followed by Trial 2 (during spring/summer months). During each trial, PAP removal efficiency (RE) was estimated

for each school by comparing concentration means for sham vs. filter classrooms. F- and t-tests were performed to determine if RE results for $PM_{2.5}$ and its constituents were statistically significant. A linear regression model was used to examine whether an association might exist between "leakiness" (air exchange) of classrooms and the RE of particles of outdoor origin.

Results: $PM_{2.5}$ concentrations were lowered in classrooms with active filters in all schools and in both trials. Mean total mass RE was 45.8% was in Trial 1 and 53.8% in Trial 2. Seasonal differences in total mass removal were significant only in School C and trivial for Schools A and B. A correlation coefficient of 0.6 showed moderate association between building leakiness and $PM_{2.5}$ of outdoor origin. F- and t-test results were significant for $PM_{2.5}$ in all schools and both trials, for S in all schools and both trials except for School B in Trial 1, for Si in School A in Trial 1 and School B in Trial 2; for Cl in School B in Trial 2, for K in both Trials in Schools A and C, and not Signficant for Ca and Fe in any school or either trial.

Conclusions: PAPs were effective in lowering concentrations of $PM_{2.5}$ and have variable effectiveness in removing its elemental constituents. More reliable results would likely be found in school buildings that are more uniform in design with classrooms that have more similar conditions than those of this study. Since $PM_{2.5}$ is associated with respiratory illness in children, PAPs may be a useful tool for lowering exposure to indoor air pollutants.

Dedication

This thesis is dedicated to my parents Margaret Smythe and the late Kelvin Smythe, both of whom always believed in me. In addition, I dedicate it to fellow tortoises everywhere who reach the finish line eventually.

Acknowledgments

I would like to thank Dr. Petros Koutrakis for his guidance in writing this thesis and for his invaluable friendship and support. I also gratefully acknowledge the help, guidance and patience of Dr. Mark Leighton. In addition, I owe a debt of gratitude to numerous friends at Harvard School of Public Health and at the Harvard Faculty of Arts and Science Department of Statistics who have encouraged me along the way, especially Dr. Gary Adamkiewicz, Ms. Joan Arnold, Dr. Yara Abu Awad, Dr. Marie-Abèle Bind, Dr. Rima Habre, Ms. Anna Kosheleva, Dr. Joy Lawrence, Ms. Tracy Mark, Dr. Marguerite Nyhan and Dr. Ibon Tamayo. I am grateful to my husband, Michael Zaisser and to my son, Rory Zaisser for being good sports throughout my master's degree undertaking. Mike has been my mainstay during tough times and has pushed me to keep forging ahead.

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Chapter I

Introduction

Most Americans, including children, spend about 87% of their time in indoor environments (Klepeis et al., 2001). A common misperception about indoor air is that it is less polluted and therefore healthier than outdoor air. In fact, pollutant levels found inside buildings can be up to five-fold higher than those found in the outdoor environment (United States Environmental Protection Agency, n.a.). It is generally accepted that outdoor air pollution poses risks to human health due to acute and chronic exposure (Pope, 2000). There is, however, ample evidence that indoor air pollution may be as important, and possibly more so, given that most people spend the majority of their time in indoor environments. In developed countries, time spent indoors exceeds 80% and is higher in the United States (Franklin, 2007; Klepeis et al., 2001). On high air pollution days, susceptible populations are advised by health professionals to remain indoors. Inside office, residential and school buildings, concentrations of various pollutants may at times exceed those of outdoor pollutants, due in part to the numerous sources of indoor pollutants.

High levels of indoor pollutants may be particularly prevalent in structures built since the 1970s which were intended to be more efficient to heat and cool, thus they are more "tightly" constructed (Thatcher, Lunden, Revzan, Sextro, & Brown, 2003). Modern, more airtight buildings have lower natural ventilation (indoor/outdoor air exchange) than older, more permeable buildings. Similarly, older buildings that have

been fitted with newer, more energy efficient windows, doors and other weatherization features such as insulation, may have lower air exchange rates than previously, thus the concentration of indoor pollutants is likely to be higher after retrofitting (Botkin & Keller, 2009). Tighter construction also means fewer outdoor pollutants may enter the building. Indoor air quality may also fluctuate seasonally depending upon whether windows are open or closed or whether or not air conditioning is used. Some outdoor air is necessary to dilute indoor air pollution emissions, therefore, a building that is fitted with a correctly installed HVAC system that utilizes outdoor air and exhaust fans and filters will likely have better indoor air quality.

As with other types of buildings, school buildings vary greatly in terms of age, condition, systems and other characteristics. The school building stock in the area in which this study takes place is quite diverse and includes school buildings that were erected in the early twentieth century as well as schools of more recent construction.

Research Significance and Goals

This aim of this study is to examine IAQ in urban schools and to assess the efficacy of PAPs as a tool to reduce childhood exposure to $PM_{2.5}$ and its constituents. There are 180 school days in the study school district's academic calendar, thus children spend much of their time in school buildings. School is in session during the colder months when windows are mostly shut. In school buildings with poor ventilation, indoor air pollution may be magnified greatly in a classroom due to high occupancy (United States Environmental Protection Agency, September, 2013). Poor ventilation in school

buildings has been associated with school absenteeism amongst children (Gaihre, Semple, Miller, Fielding, & Turner, 2014; Mendell et al., 2013)

Indoor air pollution contributes to respiratory illness in children and as such is a serious public health and environmental health issue. At the same time, fine particles emitted outdoors contribute to indoor concentrations due to infiltration by various pathways (Figure 1). Urban schools are likely to be near major roadways which increases risk of exposure and of respiratory symptoms in children (Cakmak, Mahmud, Grgicak-Mannion, & Dales, 2012).

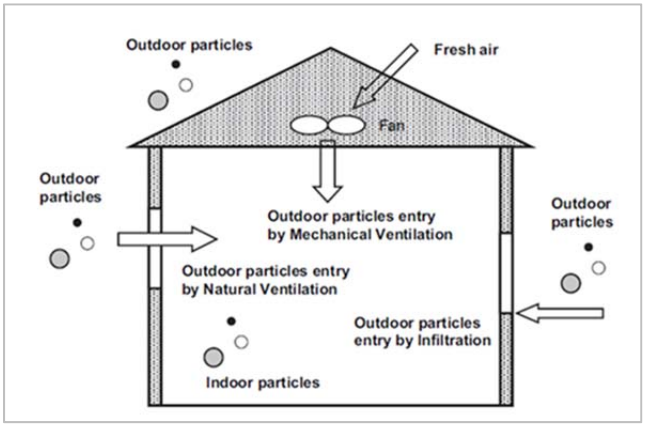

Figure 1. The pathways of outdoor particles entering into indoor environment (Chen & Zhao, 2011).

In addition, school buses and other vehicles often idle for prolonged periods directly outside schools despite ordinances that forbid this practice. When measuring indoor particulate matter, it is important to know the fraction of particles associated with outdoor pollution sources. Particulate sulfur (S) can be used as a tracer of outdoor particles (Sarnat et al., 2002). S is a regional pollutant which is emitted by coal- and oil-power plants. S is not produced by local traffic, but is transported via westerly winds

largely from Midwestern states. Also, local sources such as traffic and other small industrial sources contribute very little to ambient concentrations; therefore, S exhibits very little spatial variability within the study's geographical area.

The average infiltration rate of outdoor fine particles indoors is similar to the indoor/outdoor S concentration ratio (I/O ratio). Older, more porous buildings have higher infiltration rates. These building types would be expected therefore to have higher levels of S found on surfaces corresponding to higher outdoor sources of particulate matter.

Particles originating from indoor sources are varied in source and include animal dander, human skin, mouse fecal matter, molds, dust, cockroach allergens, etc. For example, excreted mouse allergens adhere to particles which become airborne and are very potent to children diagnosed with asthma. As many as half of inner city children are estimated to have mouse allergen sensitization (Ahluwalia & Matsui, 2011). If air purifiers are used in conjunction with the implementation of integrated pest management, biological allergens from rodents may be significantly reduced (Ahluwalia & Matsui, 2011).

Background on Pollutant Exposures and Health Effects

Exposure to air pollutants and allergens has been associated with inflammation of airways, which can lead to the onset of asthma symptoms in susceptible children (Ahluwalia & Matsui, 2011). Black carbon, a constituent of $PM_{2.5}$ which comes largely from mobile sources, has been demonstrated to induce oxidative stress in the airways of asthmatic children (Rosa et al., 2014). Various elemental constituents of $PM_{2.5}$ have also

been linked with asthmatic symptoms. Silicon (Si), iron (Fe) and calcium (Ca) (elemental constituents of $PM_{2.5}$ found in road dust), were associated with increased inhaler use in asthmatic children in a study by Gent et al. The study also found an association between potassium (K) and shortness of breath (Gent et al., 2009). Wheeze and cough symptoms have been associated with outdoor sources of indoor particulate chloride (Cl) (Habre et al., 2014). S, a product of coal burning from mid-western power plants, was found by Dai et al. to be strongly associated with respiratory causes of death in a multi-city study (Dai, Zanobetti, Koutrakis, & Schwartz, 2014).

Barnett et al. estimated that in 2007, the total costs to US society of asthma (direct costs and productivity losses) was $56 billion. Disadvantaged children may suffer disproportionately from asthma due in part to the fact that they are likelier than more affluent children to live and attend school in urban rather than suburban or rural areas (Gold & Wright, 2005; Priftis, Mantzouranis, & Anthracopoulos, 2009).

Rationale for Using PAPs in Schools

While genetic susceptibility plays a significant role in the development of asthma symptoms, there is a strong association between urban environment and reduced lung function in healthy children (Priftis et al., 2009). The rationale, therefore, for lowering indoor air pollution in schools is to prevent asthma attacks among symptomatic children and to prevent the onset of asthma in asymptomatic but potentially susceptible children. Urban schools may have budgetary limitations that preclude expensive remedial renovations. Schooldays lost due to asthma along with the burden imposed on caregivers and on society as a whole may be reduced through simpler interventions that include use

of air purifiers. The rationale for studying the effectiveness of air purifiers at the school level is that if they significantly raise the air quality in classrooms; upwards of 25 children as well as staff may benefit. The intervention will potentially benefit an entire community.

A large proportion of the indoor air quality childhood asthma intervention studies appear to have been performed in developing nations where solid fuel/biomass is used for cooking in unventilated rooms. In the United States, indoor air quality intervention studies measuring the effectiveness of air purifiers have been performed in homes, schools and other types of indoor environments that are occupied by children who are known to have asthma but to my knowledge, at the time of its conception, this is the first of its type to address the problem in the study's geographical area specifically.

Research Questions, Hypotheses and Specific Aims

Specific Aims

Specific Aim 1: The main objective of this thesis is to assess the efficiency of particle air purifiers (PAPs) in removing air pollutants inside the study school district classrooms using data that have been collected by researchers in the Department of Environmental Health at the Harvard T. H. Chan School of Public Health. These pollutants include $PM_{2.5}$, and its constituents, which include trace elements S, Si, Cl, K, Ca, and Fe.

Specific Aim 2: The objective is to determine whether seasonal differences affect the pollutant removal efficiency (RE) of air cleaners since some fraction of indoor air pollution is of indoor origin and some of outdoor origin. If, depending upon seasonal

weather conditions, with windows presumed to be generally either open or closed, what effect does this have on air purifier performance?

Hypotheses

H1 – Use of particle air purifiers decreases concentrations of $PM_{2.5}$ and its constituents measured in classrooms.

H2 – RE of $PM_{2.5}$ and its constituents will vary by season.

Chapter II

Methods

Study Locations

The main objective of this study is to demonstrate whether PAPs improve IAQ in an elementary school setting. Three elementary schools located in the same urban school district in the northeastern United States were selected to take part in a study to measure indoor air pollution concentrations. The measurement period was between October 2013 and June 2014. The three schools were designated as Schools A, B, and C. Across the three schools, there were a total of 21 classrooms. Classrooms were identified by number A1 - A8, B1 - B8 and C1 - C5. Active air cleaners with high efficiency particulate air (HEPA) filters were introduced into eleven of the classrooms. Sham cleaners (without HEPA filters and without air flow) were introduced into the remaining classrooms. Each classroom had either an active cleaner (A1 – A4, B1 – B5, C1 – C2) or a sham cleaner (A5 – A8, B6 – B8, C3 – C5).

Sampling Periods

The air in each classroom was sampled over three periods; once prior to placement of the air cleaners to get the background measurements of pollutants and twice thereafter during Trial 1 and Trial 2. The background measurement period began on 10/29/13 and ended11/04/13. Trial 1 took place during winter starting on 12/10/13 and ending on 01/28/14. Trial 2 took place during warmer weather spanning spring and early

summer starting on 04/01/14 and ending on 06/03/14. The full measurement trial schedule is displayed in Table 1.

Table 1. Summary of study sites and sampling periods.

School	Classroom (n)	Sampling period (mm/dd/yy)		
		Background	**#1 trial**	**#2 trial**
A	A1 - A8 (8)	10/29/13- 11/04/13	01/07/14- 01/17/14	04/28/14- 05/02/14
B	B1 - B8 (8)	01/10/13- 01/15/13	12/10/13- 01/17/14	04/01/14- 04/07/14
C	C1 - C5 (5)	10/15/13- 10/21/13	01/21/14- 01/28/14	05/27/14- 06/03/14

Particle Air Purifier (PAP) Model

The particle air purifier (PAP) used in the study was a Coway Woongjin Air Purifier model AP-1008BH/CH, manufactured in South Korea (Figure 2). HEPA filters were replaced every three months in active cleaners. Sham cleaners were fitted with white noise generators set to 45 decibels in order to make them indistinguishable from active cleaners, thus blinding the study from the school staff and from students. The flow rate of active cleaners was set to 110 cfm.

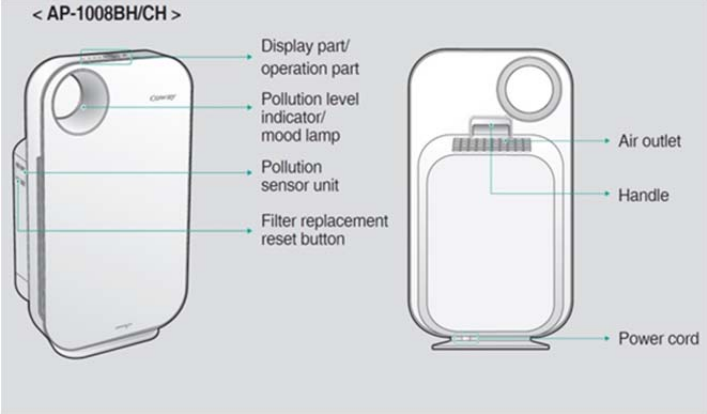

Figure 2. Coway Woongjin Air Purifier model AP-1008BH/CH.

Sampling Methods

Particle samples were collected during the intervention and sham periods and were analyzed for particle mass and elemental concentrations. A total of 63 samples were collected; 21 during the background sampling period, 22 during the two active cleaner sampling periods and 20 during the two sham sampling periods. Samples were collected on Teflon filters placed inside sample boxes. Simultaneously, daily outdoor air pollution concentrations were measured at the Harvard Supersite located on the rooftop of the Countway Library at Harvard Medical School. The Countway measurements were used as a proxy for outdoor air measurements at the school sites. This was done in order to determine the impact of outdoor pollution on IAQ (Chen & Zhao, 2011; Myers & Maynard, 2005). The rationale for this is that not many indoor sources of S exist, therefore, S is a good tracer for outdoor fine particles found indoors (Sarnat et al., 2002; Wallace & Williams, 2005). The distances of the schools from the central site at the Countway Library was 1.9, 2.5 and 0.4 miles for schools A, B, and C, respectively.

The Countway outdoor monitoring site collects air samples 24-hour/day on a cycle starting at 8:00 a.m. and ending at 7:59 a.m. the following day. The samples were

collected over several days and use a conventional inertial impactor (similar to PEMs used in classrooms) with a Teflon filter identical to those used in classrooms. A reliable estimate for PM of outdoor origin in classrooms is to use the Countway data during the classroom sampling period and to take the average over the course of those days of outdoor PM measurements.

Instrumentation for Sample Analysis

$PM_{2.5}$ particles were collected using a sampling box containing a personal exposure monitor (PEM). The PEM is an impactor which removes from the air particles of certain sizes. Sampled air enters the PEM. A greased impactor plate removes from the air sample particles with an aerodynamic diameter larger than 2.5 $\mu g/m^3$ while the smaller particles are collected downstream on a Teflon filter. The filter is weighed in a temperature and relative humidity controlled room (71 ± 3°F; 40 ± 5%) before and after sampling on an electronic microbalance (Mettler MT-5, Mettler-Toledo, Columbus, OH) to determine PM mass (gravimetric analysis).

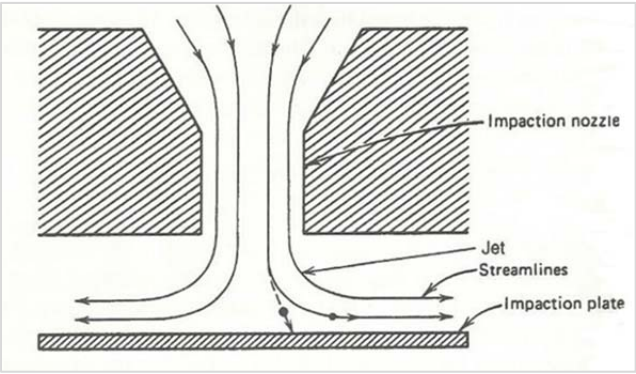

Figure 3. Conventional impactor (Hinds, 1999).

Measuring Trace Elements of $PM_{2.5}$

$PM_{2.5}$ elemental components were measured using X-Ray Fluorescence (XRF). This method uses radiation to take the electrons within atoms and disrupt their natural orbits whereby they go to a higher orbital state. Upon being "knocked down", the varying X-Rays that result are characteristic of different elements, thus the amounts of various elements collected by the filters can be determined. The XRF machine used to measure samples in this study was the Epsilon5, PaNalytical manufactured in the Netherlands.

Data Analysis:

The difference in $PM_{2.5}$ levels between the mass and sham component and active cleaner classrooms is used to establish the efficacy of the PAPs to remove $PM_{2.5}$. This was separately calculated for $PM_{2.5}$ which is the pollutant of most interest. In order to assess PAP efficacy, we also estimated the RE of total mass and particles of outdoor origin. Total mass is the total amount of particulate matter regardless of origin (indoor or outdoor).

Calculating Removal Efficiency (RE) of Total Mass

To calculate RE of total mass expressed as a percentage, the following calculation was used:

$$RE = \left(1 - \frac{\mathrm{PM_{filter}}}{\mathrm{PM_{sham}}}\right) * 100$$

Calculating RE of $PM_{2.5}$ of Outdoor Origin

To calculate RE for particles of outdoor origin expressed as a percentage the following calculation was used:

$$\mathrm{RE} = \left(1 - \frac{\text{Indoor S}_{\text{filter}}}{\text{Indoor S}_{\text{sham}}}\right) * 100$$

S is used as a surrogate for $PM_{2.5}$ of outdoor origin because it represents a large portion of $PM_{2.5}$, it is stable, and is mostly associated with outdoor sources.

Estimating Classroom Leakiness

A regression was performed to examine whether an association might exist between "leakiness" (air exchange) of classrooms and the RE of particles of outdoor origin. As leakiness increased, air cleaner effectiveness is expected to decrease. Leakiness was calculated as:

$$Leakiness = \left(\frac{sulfur_{\ indoor\ sham}}{sulfur_{\ outdoor\ Countway}}\right)$$

Calculating RE of Elements

To calculate RE for each element expressed as a percentage the following calculation was used:

$$\mathrm{RE} = \left(1 - \frac{\text{Element}_{\text{Filter}}}{\text{Element}_{\text{Sham}}}\right) * 100$$

Testing Statistical Significance of RE Results

To test whether differences between filter and sham measurements in each classroom were significant for each pollutant, we performed a t-test. To conduct a t-test,

we first have to perform an f-test to test the equal variance assumption that is required for the t-test. The level of significance of both tests (i.e., f-test and t-test) was set at 0.05. The test statistic for the f-test is:

$$F = \frac{S_x^2}{S_y^2} \text{ where } S^2 \text{ is sample variance.}$$

If the f score < 0.05, then a t-test assuming unequal variance was performed using the following t-statistic:

$$t = \frac{\bar{X}_1 - \bar{X}_2}{S_{not\ pooled}}, \text{ where S not pooled } = \sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}}$$

If the f score > 0.05, then a t-test assuming equal variance was performed using the equation below:

$$t = \frac{\bar{X}_1 - \bar{X}_2}{S_p\sqrt{\frac{2}{n}}}, \text{ where } S_p \text{ is pooled standard deviation } = \sqrt{\frac{S_{x1}^2 + S_{x2}^2}{2}}$$

A t-test p-value < 0.05 indicates that the two mean concentrations (i.e., sham and filter) are significantly different. If the mean concentrations in a room with a filter are lower than 0.05, this indicates that PAPs are effective in removing pollutants from the air of the classroom.

Chapter III

Results

$PM_{2.5}$ Measurements

$PM_{2.5}$ Background Measurements

Background measurements of $PM_{2.5}$ taken in the classrooms of the three schools (A, B, and C) prior to any intervention are displayed in Table 2 and Figure 4 below. These measurements include those taken in all classrooms prior to placement of air cleaners and prior to randomization of active or sham designations.

Table 2. Background $PM_{2.5}$ measurements.

School/room	($PM_{2.5}$)	School/room	($PM_{2.5}$)	School/room	($PM_{2.5}$)
A1	5.81	B1	6.52	C1	6.66
A2	5.70	B2	6.42	C2	7.38
A3	4.66	B3	6.51	C3	6.99
A4	~	B5	~	C4	6.34
A5	5.63	B6	6.57	C5	5.74
A6	5.66	B7	7.09	~	~
A7	5.60	B8	5.66	~	~
A8	5.96	~	~	~	~

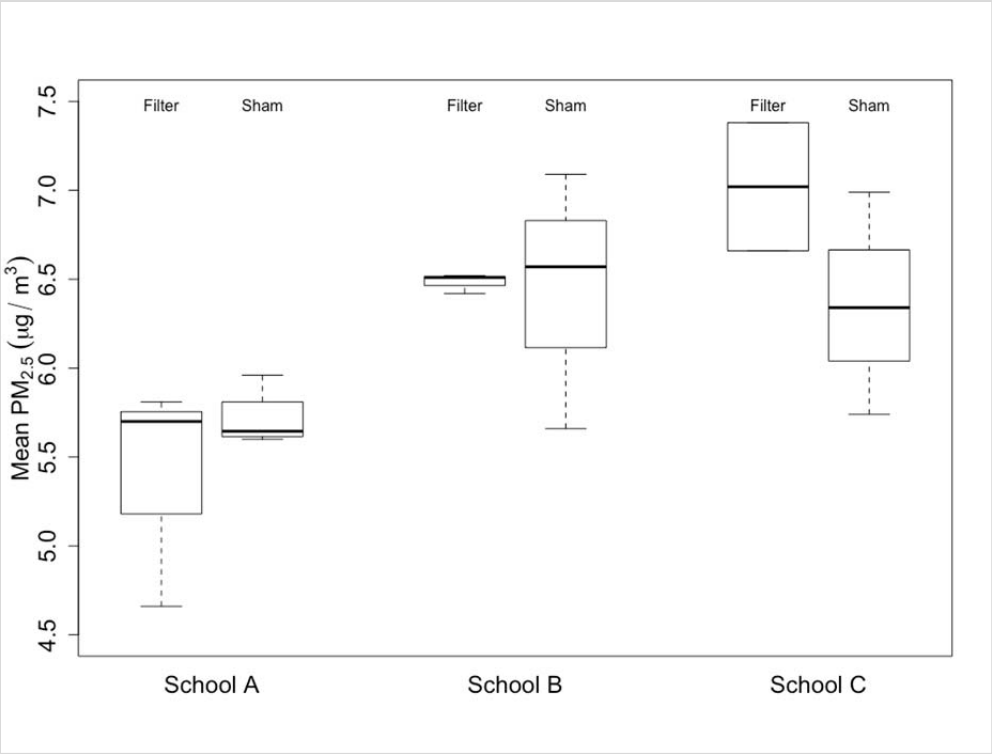

Figure 4. Background measurements of $PM_{2.5}$ mass across schools.

$PM_{2.5}$ Trial 1 Measurements

During the first sampling period (trial 1) which coincided with the cooler months (spanning fall and winter; 12/10/2013 – 01/28/2014), the air in classrooms with active purifiers across all three schools clearly had lower concentrations of $PM_{2.5}$ than those with shams as seen in figure 5. The data can be seen in Appendix 1.

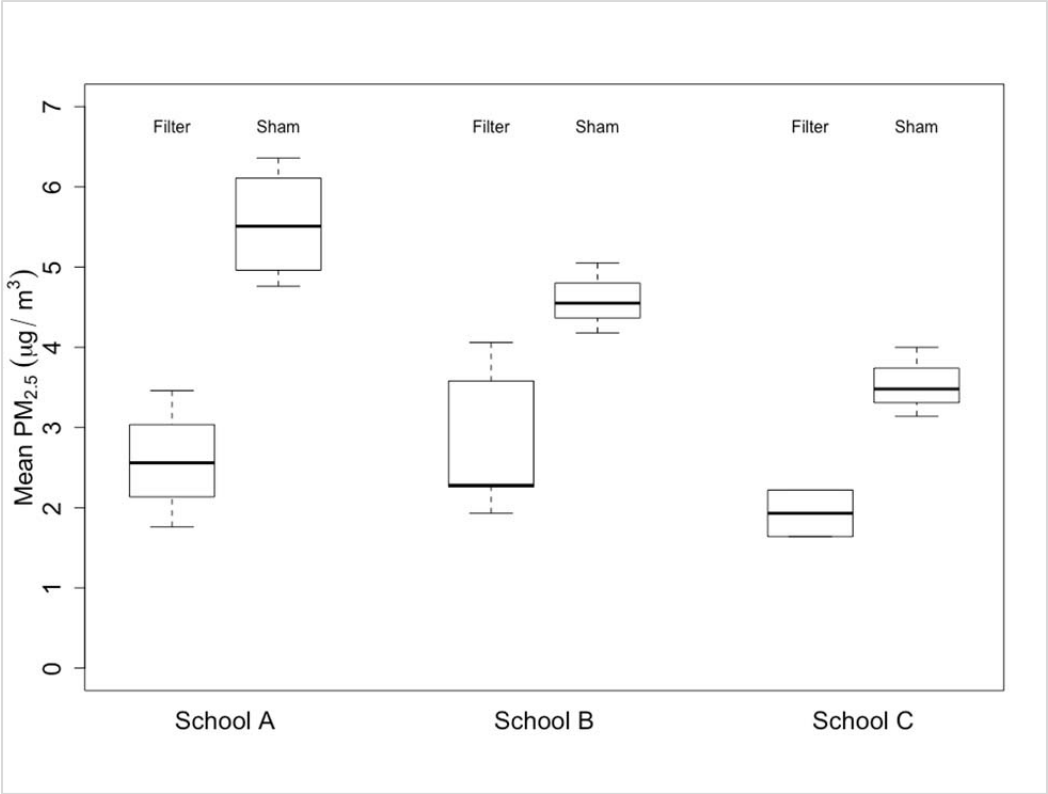

Figure 5. Trial 1 measurements of $PM_{2.5}$ across schools.

$PM_{2.5}$ Trial 2 Measurements

During the second measuring period (Trial 2) which coincided with the warmer months (spanning spring and early summer; 04/01/2014 – 06/03/2014), the air in classrooms with active purifiers across all three schools clearly had lower levels of $PM_{2.5}$ than in those classrooms with shams as shown in figure 6 below. The data can be seen in Appendix 2.

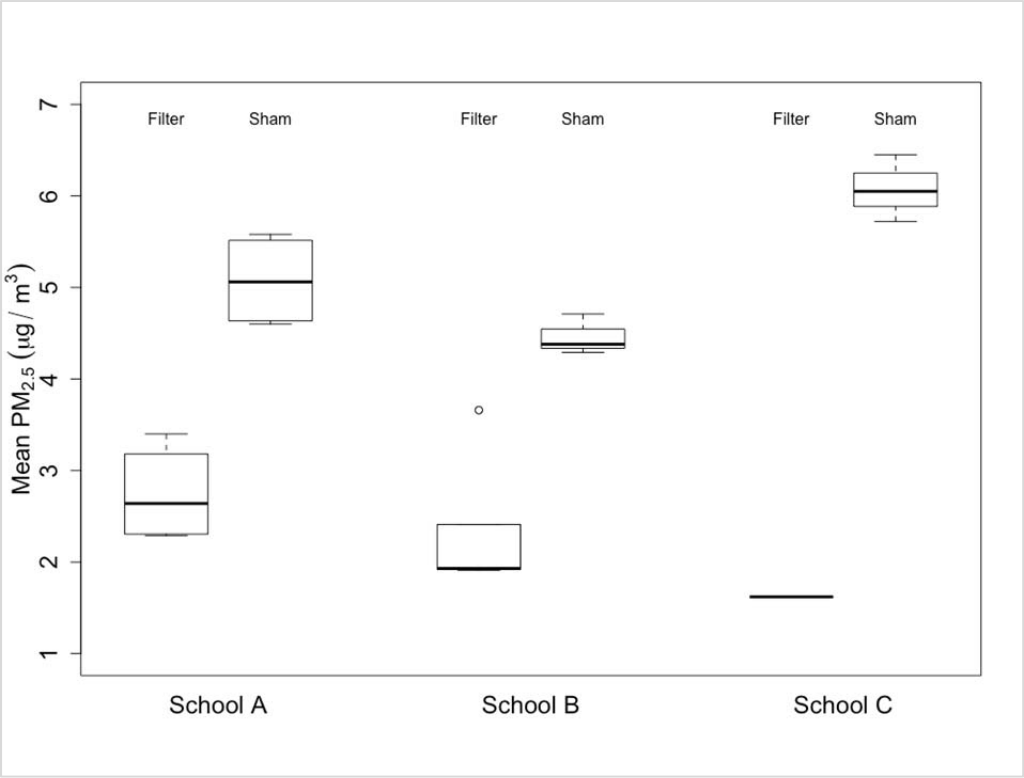

Figure 6. Trial 2 measurements of $PM_{2.5}$ across schools.

Measurement of $PM_{2.5}$ Across Schools

Figure 7 shows side-by-side box plots of filter vs. sham results for Trial Periods 1 and 2 combined. Across all three schools, the concentration of $PM_{2.5}$ is lower in the filter classrooms than in the sham classrooms. The box plots show no overlap between filter and sham in each school suggesting that the cleaners are effective in removing some portion of particulate matter in the classrooms that have the active air cleaners.

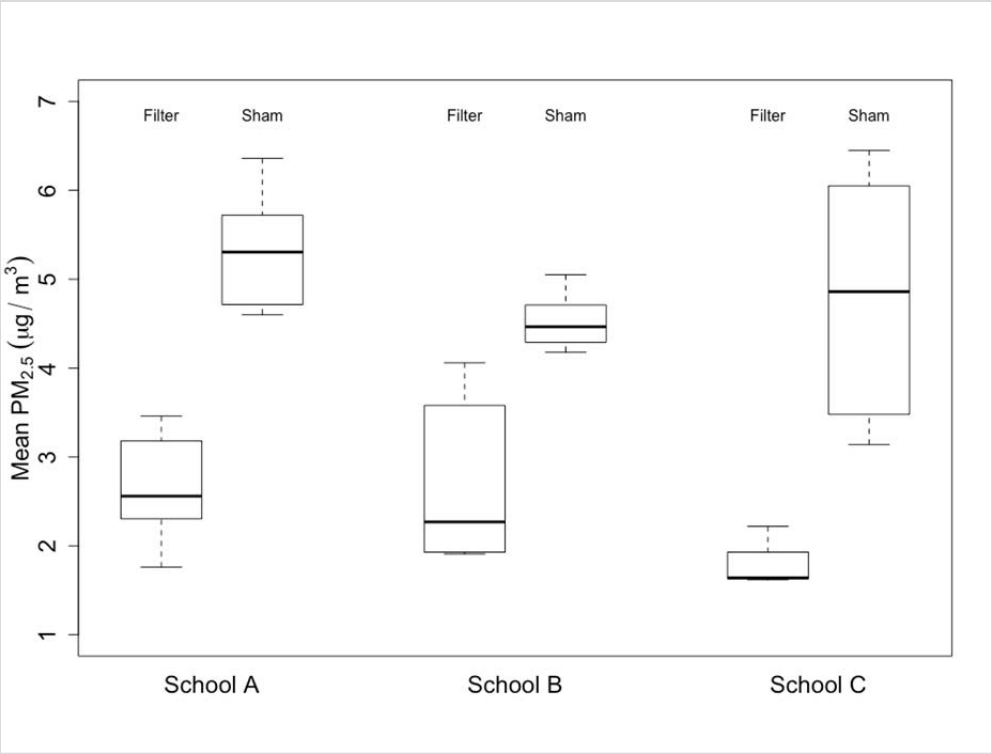

Figure 7. Measurements of $PM_{2.5}$ across schools during Trials 1 & 2 combined.

Figure 8 shows measurements for all schools combined across trials. The boxplot suggests that cleaners removed a considerable fraction of $PM_{2.5}$ in the classrooms when compared with background measurements taken in the filter and sham classrooms. Differences across trials 1 and 2 appear to be minimal. Background levels are very similar in the filter and sham classrooms across the three schools because essentially both are sham since these measurements were taken prior to implementation of PAPs in trials 1 and 2.

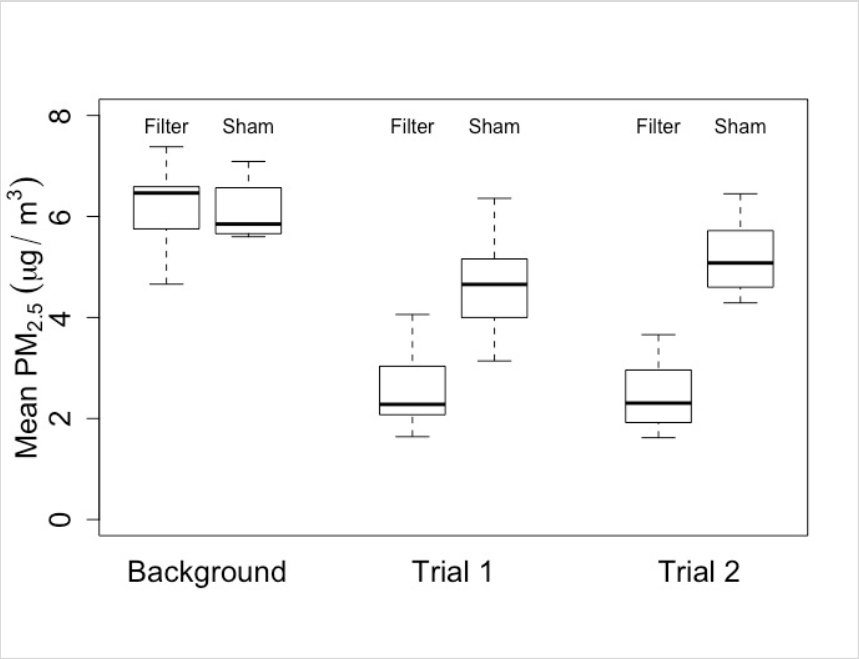

Figure 8. $PM_{2.5}$ measurements across all schools.

RE of $PM_{2.5}$ and Total Mass

Using the equation below, the mean RE of total mass by school across trials 1 (winter) and 2 (spring) was calculated, shown in table 3 and figure 9.

$$\text{Average(RE)} = \left(1 - \frac{\text{PM}_{\text{indoor filter}}}{\text{PM}_{\text{indoor sham}}}\right) * 100$$

The RE range for total mass was wide with lowest RE at 38.6% in School B during Trial 1 and highest RE at 70.9% in School C during Trial 2 (Figure 9). Average RE of total mass across schools during Trial 1 was 45.8% and 53.8% in Trial 2 (Table 3).

Using the equation below, the mean RE of $PM_{2.5}$ of outdoor origin by school across trials 1 (winter) and 2 (spring) was calculated, shown in table 3 and figure 10.

$$\text{RE} = \left(1 - \frac{\text{Indoor S}_{\text{filter}}}{\text{Outdoor S}_{\text{sham}}}\right) * 100$$

As with total mass, the RE range for $PM_{2.5}$ of outdoor origin was also wide with lowest RE at 27.7% in School B during Trial 2 and highest RE at 79.0% in School C during Trial 2 (see Figures 11 and 12). Average RE of outdoor $PM_{2.5}$ across schools during Trial 1 was 53.0% and 54.4% during Trial 2 (Table 3).

Table 3. RE of total mass and outdoor $PM_{2.5}$ by school.

% Mean RE of total mass by school				
	A	B	C	Mean
Trial 1	53.3	39.0	45.5	45.8
Trial 2	46.0	44.5	70.9	53.8
Mean	50.0	42.0	58.2	
% Mean RE of $PM_{2.5}$ of outdoor origin by school				
	A	B	C	Mean
Trial 1	60.5	28.2	70.2	53.0
Trial 2	56.5	27.7	79.9	54.4
Mean	58.5	28.0	74.6	

A small decrease was seen in mean RE of total mass in School A from winter of 53.3 % during Trial 1 compared with 46.0 % measured at the end of the trial period 2 in the Spring. This does not appear to be the case however with Schools B and C. These schools showed a reversal of the case of School A (Figure 9).

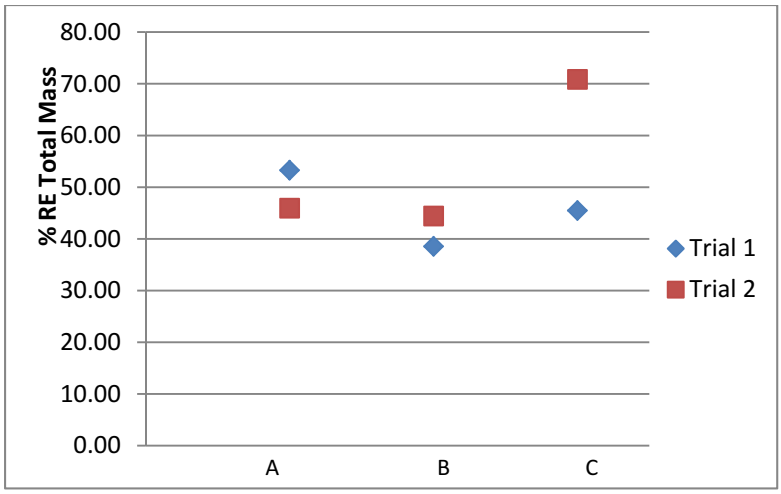

Figure 9. Percentage mean RE of total mass displayed by school.

Air purifiers in School B were 7.3 percentage points more efficient during the spring than during winter at removing total mass, while air purifiers in School C were 25.4 percentage points more efficient in the spring at removing total mass. It was observed in both trials 1 and 2 that the mean RE of total mass was high in schools A and C, but was lower in school B (Figure 10).

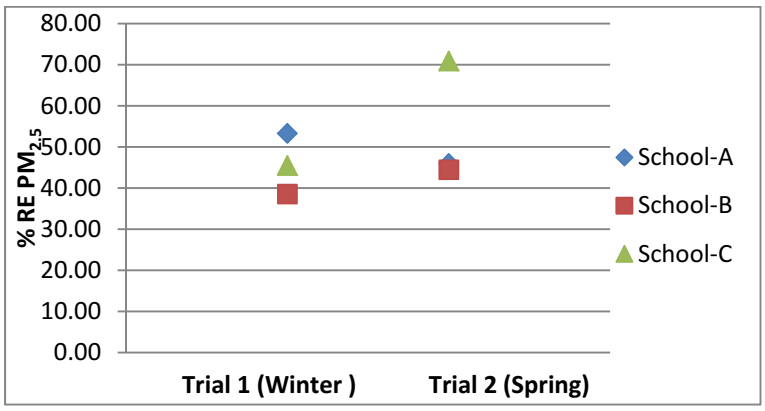

Figure 10. Percentage mean RE of total mass displayed by season.

The smallest RE for $PM_{2.5}$ of outdoor origin was observed in School B during Trial 1 and Trial 2 (28.2% and 27.7% respectively) and on average since very little difference was observed in School B between trials. This indicates trivial seasonal difference for School B (Figure 11).

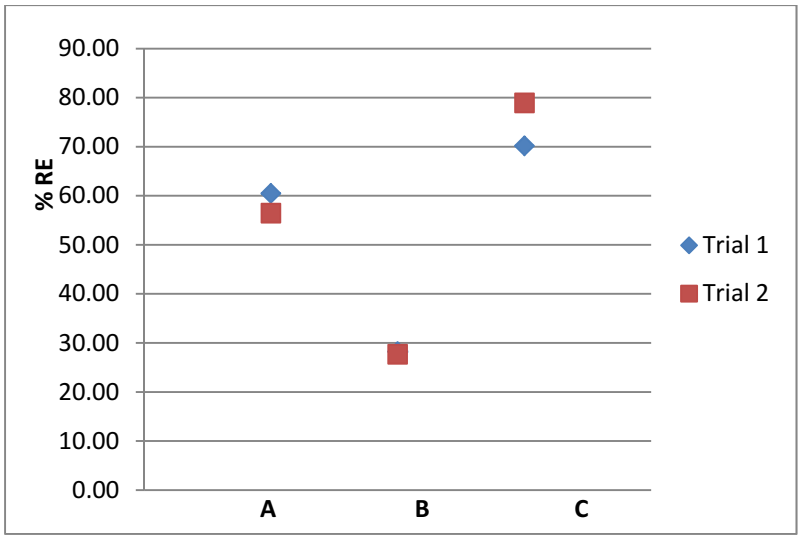

Figure 11. Percentage mean RE of outdoor $PM_{2.5}$ displayed by school.

School C had the highest RE in each trial for outdoor $PM_{2.5}$ (70.2% and 79.0% for Trials 1 and 2, respectively) and on average. In addition, School C showed higher RE during the warmer period of Trial 2. As with School B, higher RE was observed in Trial 1 in School A (Figure 12).

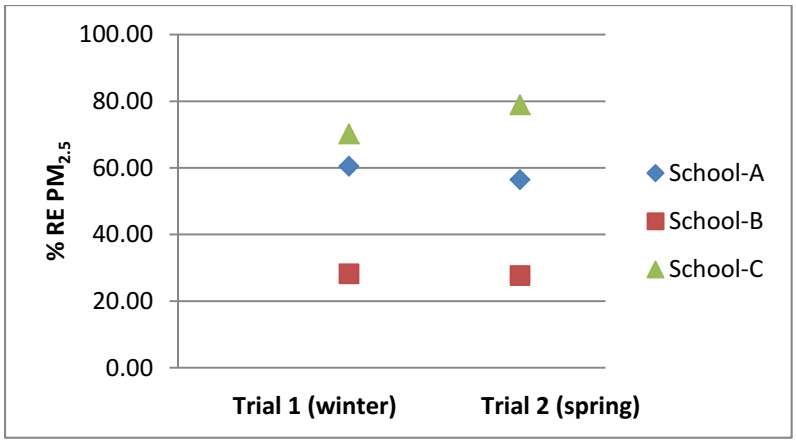

Figure 12. Percentage mean RE of outdoor $PM_{2.5}$ displayed by season.

To test if there was an association between "leakiness" (air exchange) and RE of total mass, a regression was performed using Microsoft Excel. Data points for leakiness and RE of outdoor PM were converted to logarithms in order to normalize distribution of the residuals. This equation below shows how the calculated RE was regressed against log leakiness:

$$RE = \alpha + ß^* \log (L) + e$$

Where:

RE = removal efficiency of outdoor PM2.5

α = intercept

ß = coefficient

L = leakiness

e = error term

"Leakiness" was calculated using the following equation:

$$Leakiness = \left(\frac{sulfur_{\ indoor\ sham}}{sulfur_{\ outdoor\ Countway}} \right)$$

Table 4. Data used to determine correlation between "leakiness" and RE of total mass.

School/Trial	Leakiness	Leakiness (log)	RE Outdoor PM	RE Outdoor PM (log)
A/1	0.70	-0.1549	60.50	1.781755
B/1	0.64	-0.19382	28.21	1.450403
C/1	0.77	-0.11351	70.19	1.846275
A/2	0.85	-0.07058	56.48	1.751895
B/2	0.60	-0.22185	27.71	1.442637
C/2	0.74	-0.13077	78.96	1.897407

The R^2 statistic was 0.60~ which shows moderate association between leakiness of the classrooms and the RE of particles of outdoor origin. However, as can be seen from the graph below in figure 13, the direction of the slope is positive whereas it was expected to be negative. That is, the graph seems to indicate that as leakiness increases, efficiency also increases which is an unexpected and non-intuitive result. Possible explanations for this are laid out in the discussion section.

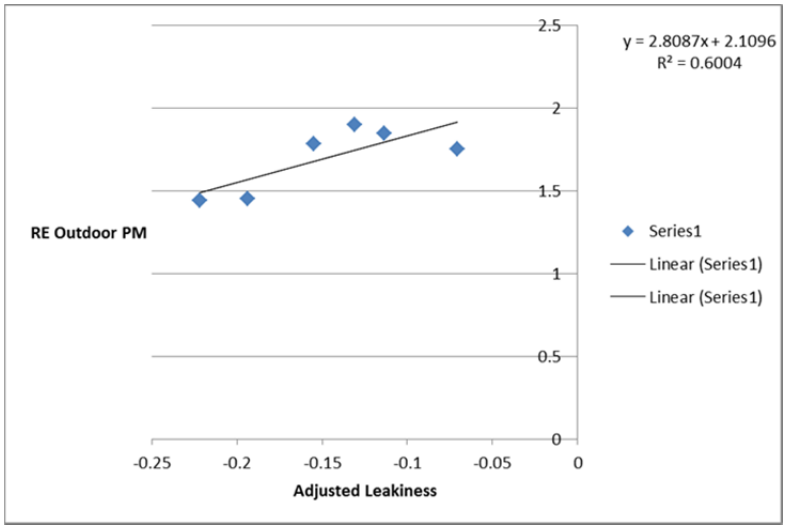

Figure 13. Association between building leakiness and RE of outdoor PM.

Elements

Background Measurements of Elements

Background measurements of elements taken in the classrooms of the three schools (A, B, and C) prior to any intervention are displayed in Table 5 and Figures 15 and 16. These measurements include those taken in all classrooms prior to placement of air cleaners and prior to randomization of active or sham designations.

Table 5. Background measurement of elements ($\mu g/m^3$).

Room	**S**	**Si**	**Cl**	**K**	**Ca**	**Fe**
A1	0.329	0.022	0.023	0.036	0.021	0.086
A2	0.328	0.012	0.013	0.044	0.017	0.050
A3	0.243	0.013	0.012	0.026	0.015	0.033
A5	0.308	0.013	0.015	0.033	0.016	0.046
A6	0.306	0.019	0.007	0.030	0.017	0.046
A7	0.346	0.014	0.015	0.034	0.022	0.053
A8	0.347	0.010	0.015	0.036	0.019	0.051
B1	0.475	0.038	0.017	0.027	0.028	0.057
B2	0.466	0.024	0.015	0.024	0.021	0.035
B3	0.448	0.065	0.004	0.021	0.017	0.031
B6	0.435	0.039	0.020	0.024	0.027	0.059
B7	0.436	0.028	0.012	0.023	0.024	0.046
B8	0.241	0.025	0.085	0.030	0.034	0.047
C1	0.394	0.038	0.015	0.025	0.032	0.046
C2	0.339	0.035	0.013	0.020	0.033	0.038
C3	0.460	0.020	0.002	0.026	0.023	0.038
C4	0.412	0.022	0.013	0.023	0.042	0.048
C5	0.430	0.018	0.006	0.021	0.023	0.039

S is presented in a separate box plot in Figure 14 due to the fact that measurements for this element were on a different scale. S levels collected by PAPs were much higher than other elements and it was therefore difficult to present all six elements in a single graphic.

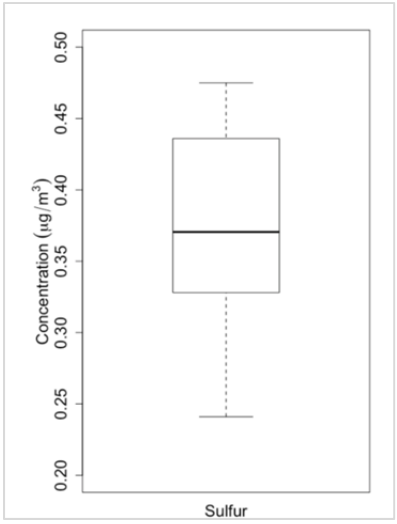

Figure 14. Boxplot of background measurements of S.

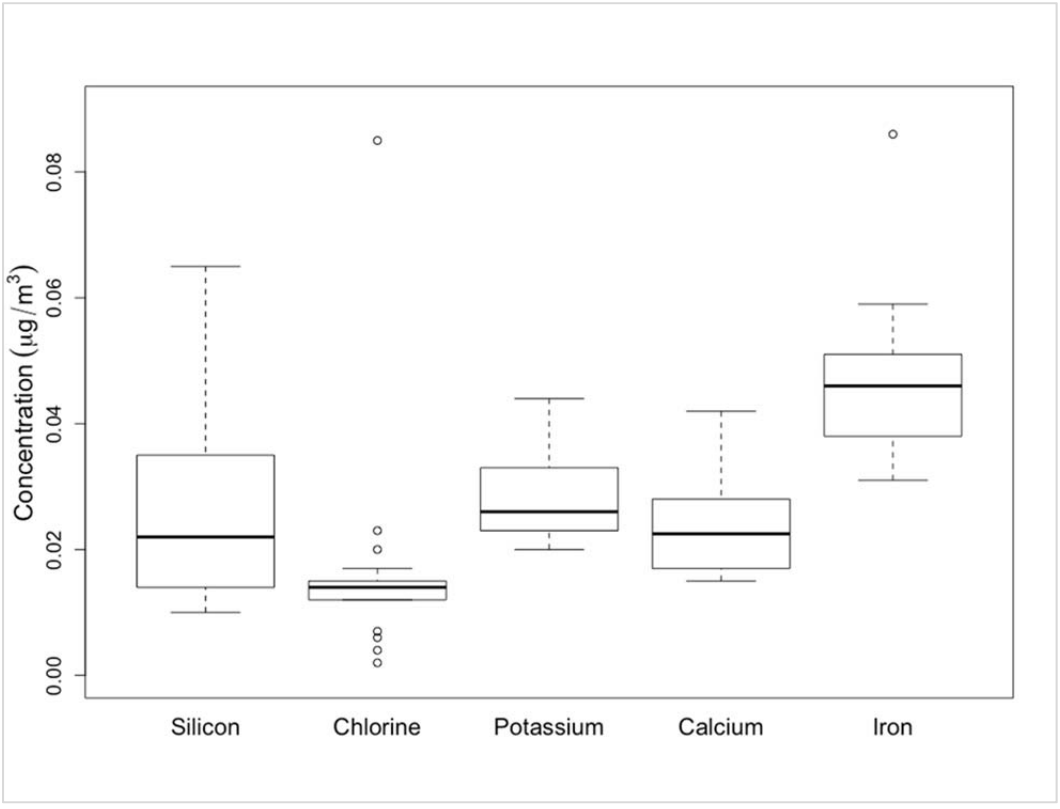

Figure 15. Boxplots of background measurements of Si, Cl, K, Ca and Fe.

Figures 16 - 21 show boxplot filter vs sham comparisons of measurements of elements comprising both trials combined. Appendix A and B provide the data used to make these boxplots. Differences in filter vs. sham elemental pollutant measurements are most apparent with S and K. For S and K this difference is big because these elements come from outdoor sources. For the other elements with small differences between filter vs. sham elemental pollutant measurements, this is due to these elements being largely of indoor origin that are resuspended as dust.

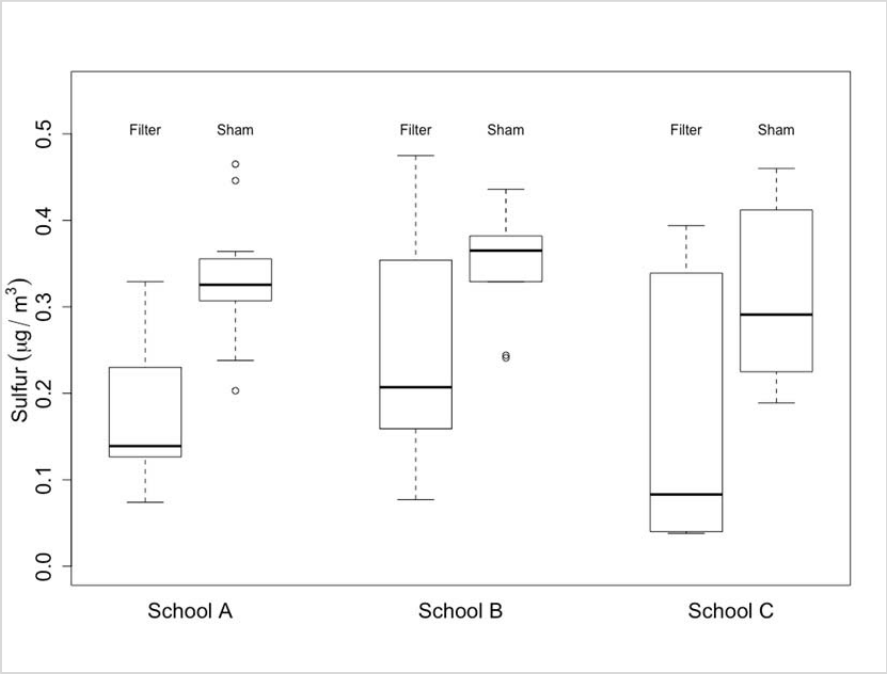

Figure 16. S measurements across schools comparing concentrations when using a filter vs sham.

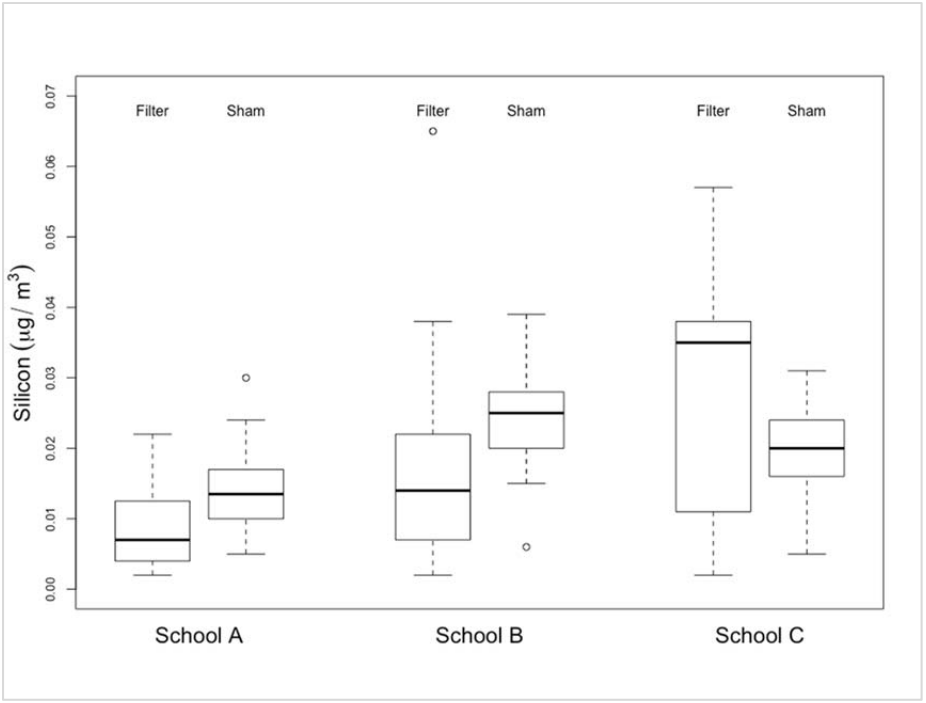

Figure 17. Si measurements across schools comparing concentrations when using a filter vs sham.

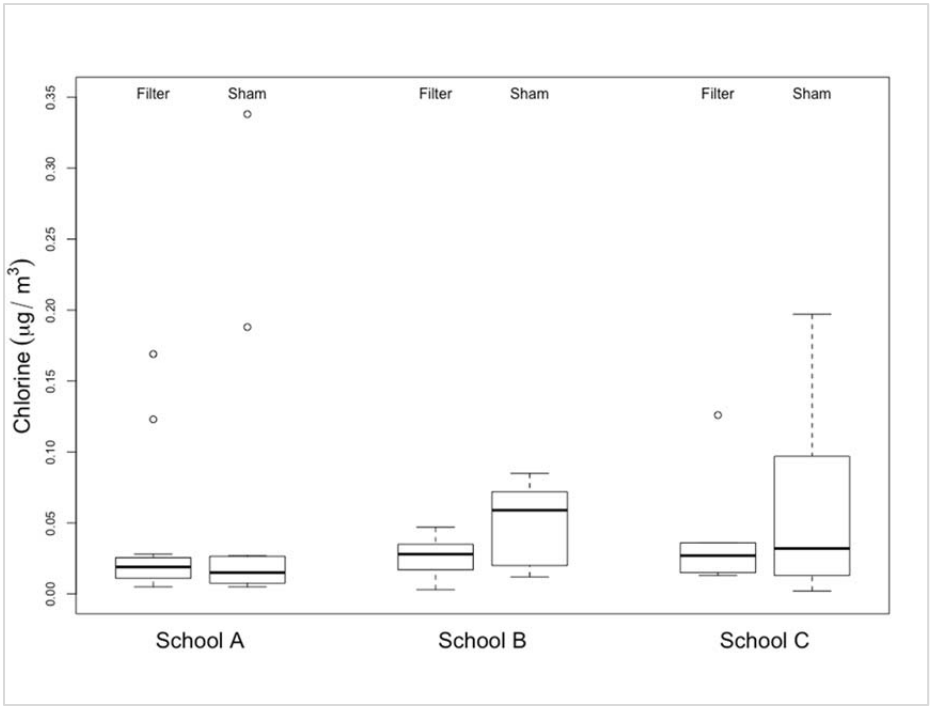

Figure 18. Cl measurements across schools comparing concentrations when using a filter vs sham.

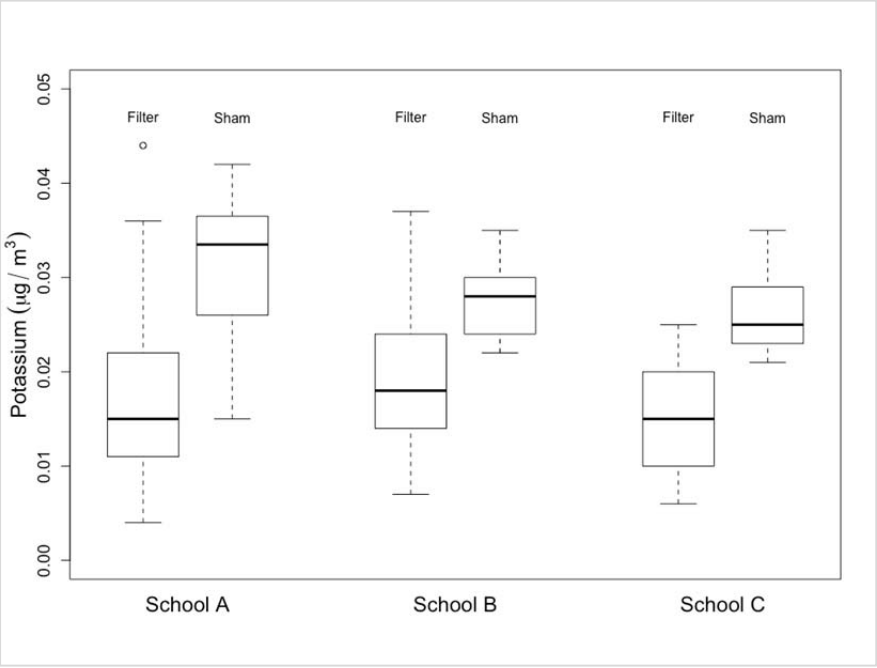

Figure 19. K measurements across schools comparing concentrations when using a filter vs sham.

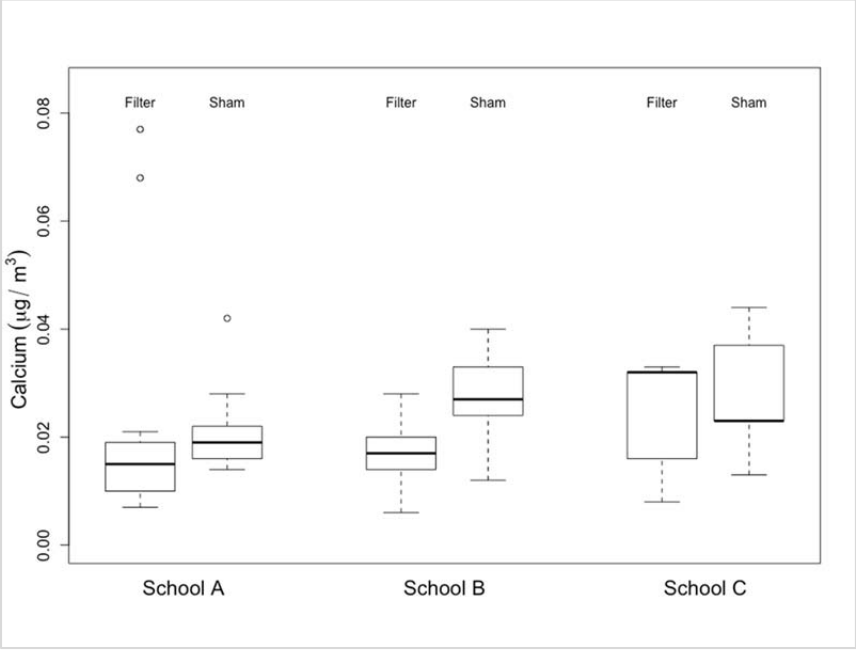

Figure 20. Ca measurements across schools comparing concentrations when using a filter vs sham.

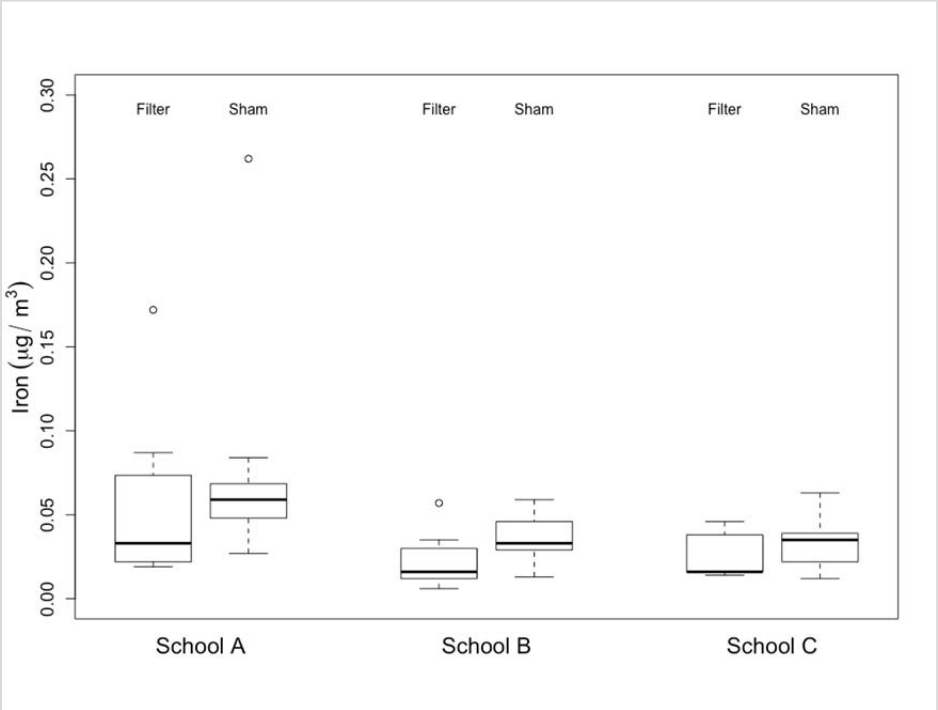

Figure 21. Fe measurements across schools comparing concentrations when using a filter vs sham.

RE for Elements

For each element the RE of the air purifiers was calculated using the formula

$$RE = 1 - \left(\frac{Element_{Filter}}{Element_{Sham}}\right) * 100$$

RE results are below in Table 6 for each element in all schools and both trials.

Table 6. RE for elements during Trial 1 and Trial 2 combined.

Trial	School	S	Si	Cl	K	Ca	Fe
1	A	60.5	45.5	31.7	58.7	-27.2	-19.2
1	B	28.2	47.3	37.0	28.0	51.5	34.8
1	C	70.2	25.0	48.1	66.5	34.5	18.2
Trial 1 Average		53.0	39.3	38.9	51.1	19.6	11.3
SD		22.0	12.4	8.4	20.4	41.4	27.7
2	A	56.5	59.5	38.8	59.5	-12.8	77.5
2	B	27.7	43.8	40.5	46.0	23.1	44.3
2	C	79.0	-39.4	13.2	64.6	33.3	64.8
Trial 2 Average		54.4	21.3	30.8	56.7	14.5	62.2
SD		25.7	53.2	15.3	9.6	24.2	16.8
Combined Trials Average		53.7	30.3	34.9	53.9	17.1	36.7
SD		21.4	35.9	11.9	14.6	30.5	34.6

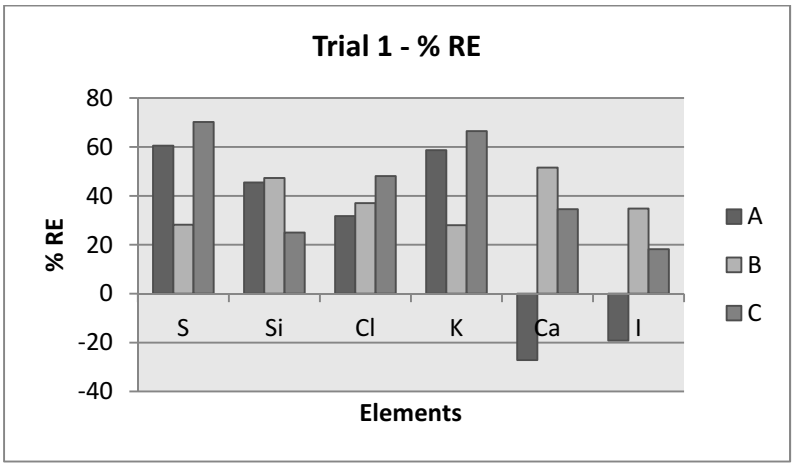

Figure 22. Percentage of RE of elements during Trial 1.

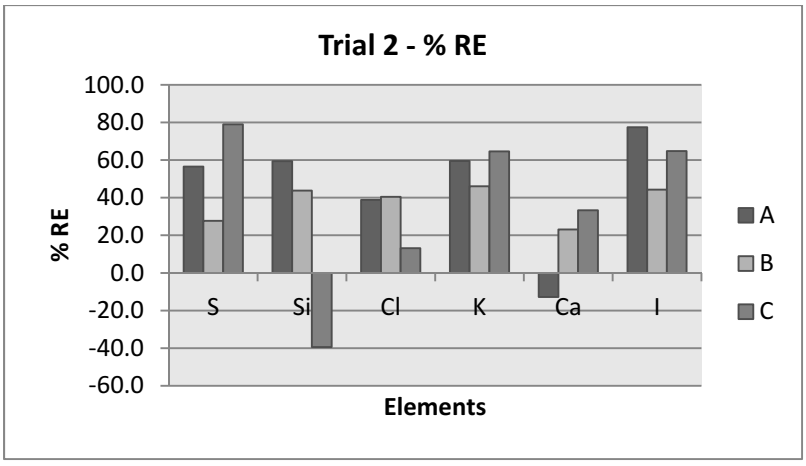

Figure 23. Percentage of RE of elements during Trial 2.

F-Test and T-Test Results

RE for $PM_{2.5}$ was found to be statistically significant for Schools A, B, and C during both Trials 1 and 2. RE for S was statistically significant for Schools A and C during Trial 1 and in Schools A, B, and C during Trial 2. RE for Si was statistically significant in School A during Trial 1 and in School B in Trial 2. RE for Cl was statistically significant in School B, Trial 2 and RE for K was statistically significant in Schools A and C during Trials 1 and 2. There was no statistical significance for RE in any school during either trial for Ca and Fe. F-test and t-test scores may be seen in Table 7.

Table 7. F-test and T-test scores for $PM_{2.5}$ and constituents.

Trial 1				Trial 2			
Pollutant	School	F-test P < 0.05	T-test P < 0.05	Pollutant	School	F-test P < 0.05	T-test P < 0.05
	A	0.968	0.001		A	0.940	0.001
	B	0.381	0.045		B	0.114	0.028
$PM_{2.5}$	C	0.887	0.025	$PM_{2.5}$	C	0.759	0.001
	A	0.361	0.002		A	0.366	0.009
	B	0.841	0.307		B	0.299	0.011
S	C	0.468	0.006	S	C	0.988	0.005
	A	0.841	0.022		A	0.530	0.145
	B	0.957	0.296		B	0.891	0.048
Si	C	0.844	0.734	Si	C	0.045	0.638
	A	0.254	0.495		A	0.245	0.566
	B	0.298	0.519		B	0.896	0.008
Cl	C	0.697	0.241	Cl	C	0.282	0.213
	A	0.303	0.000		A	0.403	0.010
	B	0.716	0.376		B	0.716	0.376
K	C	0.373	0.015	K	C	0.336	0.001
	A	0.030	0.728		A	0.139	0.876
	B	0.082	0.115		B	0.089	0.129
Ca	C	0.076	0.278	Ca	C	0.382	0.100
	A	0.008	0.683		A	0.000	0.245
	B	0.951	0.407		B	0.841	0.075
Fe	C	0.357	0.483	Fe	C	0.946	0.280

Chapter IV

Discussion

$PM_{2.5}$

Trial 1 measurements were taken during cold weather months between 12/10/2013 and 01/28/2014. The air in the classrooms with active purifiers across all three schools had lower levels of $PM_{2.5}$ than those classrooms that had shams. This provides evidence that the air purifiers are effective in removing some proportion of $PM_{2.5}$ from the indoor air of the "active" classrooms during Trial 1. Similarly, during Trial 2 which corresponded to warmer months (04/01/2014 – 06/03/2014), the air in the classrooms with active purifiers across all three schools clearly had lower levels of $PM_{2.5}$ than on those classrooms with shams. This provides evidence that the air purifiers are also effective in removing some proportion of $PM_{2.5}$ from the indoor air of the "active" classrooms during trial 2.

Seasonal differences in RE are small for $PM_{2.5}$ of outdoor origin but greater for total mass. While RE results for $PM_{2.5}$ are fairly consistent across seasons, they are less consistent across schools. As noted in the results section, PAPs were more efficient in schools B and C during the warmer months of Trial 2 than in the cooler months of Trials 1. Conversely RE in School A decreased from Trial 1 to Trial 2, which is consistent with the expectation that windows would be closed in order to retain heat and that buildings would be tighter during the colder season, thus a smaller volume of air would escape out of the windows (less "leakiness" or air exchange) that would otherwise be collected by

the filter. However, while this is often true, it may not always be the case. For example, wind can affect air exchange in buildings even with closed windows, particularly if buildings are not well sealed. One possible explanation for the unexpected results in schools B and C is that certain classrooms may overheat during the winter months forcing occupants to open the windows to achieve a more comfortable indoor air temperature. In addition, the temperature differential between indoor and outdoor air may help to increase air exchange if the building is not well sealed.

As already noted in the results section, the range in RE across schools and classrooms for total mass and $PM_{2.5}$ of outdoor origin was quite wide. Since none of the buildings or classrooms were identical, this is likely to be due in part to differences in building design and materials, classroom orientation with respect to solar heat, building heating efficiency, school bus schedules, local traffic proximity and patterns as well as possible human intervention (e.g.; teachers may turn PAPs off due to noise) along with other uncontrolled circumstances.

Elements

RE results for elements were variable. PAPs appear to be less efficient at removing certain elements from indoor air than they are at removing $PM_{2.5}$. Elements are constituents of PM (not physically distinct or separate from PM). In spite of the elements of interest in this study being generally above the method detection limits, the RE was statistically significant for only a few elements in certain schools. It is likely that for some these elements, the fact that they have important indoor sources (e.g. resuspended dust), explains these results. Differences in filter vs. sham elemental

pollutant measurements are most apparent and were largely statistically significant with S and K. For these two elements the difference is big because a large proportion of these come from outdoor sources with only a small proportion from indoors. K found indoors comes from activities such as biomass burning (Amato et al., 2014) and with S the main source is industrial activity. That RE for S should be high is not surprising since it is used as a surrogate for outdoor $PM_{2.5}$.

RE for Ca was -27.2% during Trial 1 in School A and -12.8% during Trial 2 in School A. These negative numbers seem non-intuitive since RE is a percentage. If a positive RE result indicates that PAPs remove a proportion of particles from indoor air, then a negative RE result would imply that PAPs are in some way responsible for adding this element back into the classroom, which is not possible. One likely explanation may be related to conditions in this school and some input of Ca that PAPs' ability to remove cannot keep up with. Possibly there is a greater reliance by teachers on chalk boards at this school (vs white boards, smart boards or other teaching tools) which, if used with chalk and cleaned often, would produce a lot of suspended particulate matter that contain high levels of Ca (Canha et al., 2010). RE for Fe during Trial 2 in School A was also negative at -12.8%. RE for Si during Trial 2 in School C was -39.4. When estimating RE, an assumption is made that shams are the reference and that sham and non-sham rooms are comparable. In other words, the assumption is that the main difference between the rooms is presence or absence of an active PAP. This may not always be the case and may be problematic for elements with significant indoor sources.

Limitations of the Study

School B is different in its architectural design to schools A and C and was built according to the "open classroom" model. The classroom partitions are temporary and removable, and when in place do not reach the ceiling. Therefore there is air exchange between abutting "classrooms". This means that the air was possibly more dilute with longer particle suspension times and slower deposition. PAPs would possibly have to run for longer periods to collect pollutant levels similar to those at Schools A and C. PAPs are probably better suited for smaller spaces with less air volume. A central air filtration system is probably a more suitable remedy (though more costly to install and operate) for removing indoor air pollution in large, wide-open interior spaces.

Conditions between the three schools may differ in terms of school bus drop-off and pick-up locations and proximity to school buildings. These differences may affect concentrations of outdoor PM that can penetrate the buildings. School body size might also be taken into account since the greater number of students who must be transported to and from school by school bus, the greater number of buses will stop in the drop-off and pick-up areas.

A limitation of the analysis to determine if leakiness of buildings correlates with PAP efficiency lies in the small number of data points in the linear regression. While the R^2 results in the regression analysis show evidence of moderate association, this statistic would have been more reliable if more data had been available. Bigger studies with longer sampling periods and a greater number of schools and of classrooms would likely yield more definitive and reliable results.

Conclusions

PAPs removed $PM_{2.5}$ from the air of every classroom in all three schools in which active cleaners with filters were placed to varying degrees. RE was statistically significant for $PM_{2.5}$ in all schools and in all classrooms with active PAPs. While seasonal differences do not appear to have been very strong in terms of RE of $PM_{2.5}$, differences by school were more apparent. Similarly, a statistically significant reduction in S and K in indoor air was observed in this study, and to a lesser extent Si and Cl.

PAPs may be a worthwhile investment for inner-city schools located in high air pollution areas on major roadways since they are effective in removing $PM_{2.5}$ from indoor air and to a lesser degree, certain elemental constituents of $PM_{2.5}$. Several studies are currently attempting to address the question that reducing levels of indoor air pollutants will result in improved health outcomes for children. The use of PAPs in schools where many children may benefit may be used as part of a broader effort to reduce childhood exposures to harmful air pollutants.

Appendix 1. Concentrations of $PM_{2.5}$ in Schools A, B, and C during Trial 1

School	Classroom	($PM_{2.5}$) Mean µg/m^3	SD µg/m^3	Median µg/m^3
A	A1	2.61	1.12	2.42
	A2	3.46	2.95	2.54
	A3	1.76	0.48	1.72
	A4	2.51	0.87	2.47
	A5	4.76	2.48	4.17
	A6	5.16	2.44	4.20
	A7	5.86	2.53	5.44
	A8	6.36	2.65	5.88
	Total	**4.06**	**1.94**	**3.61**
B	B1	4.06	1.36	4.06
	B2	2.26	0.55	2.39
	B3	2.28	0.82	2.35
	B4	3.58	0.82	3.64
	B5	1.93	0.55	1.85
	B6	4.55	1.22	4.67
	B7	4.18	0.82	4.19
	B8	5.05	1.40	5.36
	Total	**3.49**	**0.94**	**3.56**
C	C1	2.22	0.64	2.02
	C2	1.64	0.64	1.43
	C3	3.48	1.03	3.35
	C4	3.14	1.30	2.56
	C5	4.00	1.20	3.86
	Total	**2.90**	**0.96**	**2.64**

Appendix 2. Concentrations of $PM_{2.5}$ in Schools A, B, and C during Trial 2

School	Classroom	($PM_{2.5}$) Mean $\mu g/m^3$	SD $\mu g/m^3$	Median $\mu g/m^3$
A	A1	2.96	1.00	2.68
	A2	2.32	0.90	1.85
	A3	2.29	0.78	2.00
	A4	3.40	3.31	2.39
	A5	5.58	1.34	5.55
	A6	4.60	1.04	4.64
	A7	5.45	2.34	4.59
	A8	4.67	1.51	4.04
	Total	**3.91**	**1.53**	**3.47**
B	B1			
	B2	1.91	0.41	1.95
	B3	3.66	0.94	3.91
	B4	2.41	0.46	2.38
	B5	1.93	2.68	1.85
	B6	4.38	0.98	4.39
	B7	4.29	1.63	4.48
	B8	4.71	1.79	4.56
	Total	**3.33**	**1.27**	**3.36**
C	C1	1.92	0.76	1.68
	C2	1.62	1.35	1.23
	C3	6.05	1.63	6.16
	C4	5.72	1.07	5.46
	C5	6.45	1.75	6.08
	Total	**4.35**	**1.31**	**4.12**

Appendix 3. Concentrations of indoor trace elements in Schools A, B, and C during Trial 1

		Elements (μg/m3)					
School	Classroom	S	Si	Cl	K	Ca	Fe
A	A1	0.134	0.004	0.009	0.015	0.009	0.172
	A2	0.217	0.004	0.005	0.018	0.017	0.061
	A3	0.139	0.007	0.010	0.016	0.009	0.022
	A4	0.127	0.009	0.019	0.015	0.068	0.087
	A5	0.333	0.010	0.027	0.040	0.016	0.071
	A6	0.318	0.011	0.026	0.037	0.015	0.066
	A7	0.446	0.009	0.005	0.036	0.022	0.066
	A8	0.465	0.014	0.005	0.042	0.028	0.084
	Mean	0.272	0.009	0.013	0.027	0.023	0.079
	Stdev	0.130	0.003	0.009	0.011	0.018	0.040
B	B1	0.354	0.005	0.047	0.037	0.015	0.016
	B2	0.161	0.004	0.035	0.015	0.014	0.012
	B3	0.201	0.002	0.018	0.018	0.006	0.006
	B4	0.287	0.018	0.003	0.024	0.014	0.030
	B5	0.148	0.007	0.025	0.014	0.014	0.011
	B6	0.382	0.020	0.084	0.035	0.040	0.033
	B7	0.244	0.006	0.015	0.022	0.012	0.013
	B8	0.336	0.015	0.023	0.033	0.026	0.023
	Mean	0.264	0.010	0.031	0.025	0.018	0.018
	Stdev	0.090	0.007	0.025	0.009	0.011	0.010
C	C1	0.083	0.011	0.126	0.015	0.016	0.014
	C2	0.040	0.002	0.036	0.006	0.008	0.016
	C3	0.225	0.016	0.197	0.035	0.019	0.022
	C4	0.205	0.005	0.097	0.029	0.013	0.012
	C5	0.189	0.005	0.174	0.030	0.023	0.021
	Mean	0.149	0.008	0.126	0.023	0.016	0.017
	Stdev	0.082	0.006	0.064	0.012	0.006	0.004

Appendix 4. Concentrations of indoor trace elements in Schools A, B, and C during Trial 2

School	Classroom	Elements (μg/m^3) S	Si	Cl	K	Ca	Fe
A	A1	0.173	0.018	0.019	0.012	0.011	0.028
	A2	0.074	0.002	0.028	0.004	0.007	0.022
	A3	0.114	0.003	0.123	0.008	0.011	0.022
	A4	0.126	0.007	0.169	0.010	0.077	0.019
	A5	0.364	0.024	0.020	0.026	0.019	0.050
	A6	0.314	0.030	0.008	0.017	0.014	0.262
	A7	0.238	0.015	0.338	0.026	0.042	0.065
	A8	0.203	0.005	0.188	0.015	0.019	0.027
	Mean	0.201	0.013	0.112	0.015	0.025	0.062
	Stdev	0.094	0.010	0.109	0.007	0.022	0.077
B	B2	0.159	0.014	0.041	0.013	0.019	0.012
	B3	0.261	0.019	0.047	0.020	0.020	0.027
	B4	0.207	0.010	0.035	0.015	0.017	0.021
	B5	0.119	0.014	0.035	0.011	0.026	0.015
	B6	0.367	0.026	0.072	0.029	0.033	0.041
	B7	0.329	0.020	0.059	0.025	0.019	0.029
	B8	0.365	0.030	0.068	0.028	0.028	0.031
	Mean	0.258	0.019	0.051	0.020	0.023	0.025
	Stdev	0.100	0.007	0.015	0.007	0.006	0.010
C	C1	0.077	0.022	0.028	0.007	0.020	0.015
	C2	0.038	0.057	0.027	0.010	0.032	0.016
	C3	0.294	0.030	0.032	0.023	0.036	0.034
	C4	0.291	0.031	0.028	0.024	0.037	0.035
	C5	0.235	0.024	0.035	0.025	0.044	0.063
	Mean	0.187	0.033	0.030	0.018	0.034	0.033
	Stdev	0.121	0.014	0.003	0.008	0.009	0.020

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