Impact and benefits of the air cleaning measures implemented in two schools

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ABSTRACT

A Canadian provincial government has initiated a collaboration with the Indoor Air Quality (IAQ) team of the National Research Council of Canada (NRC) to conduct a controlled intervention study to determine the effectiveness of portable air cleaners (PACs) in reducing indoor air contaminants in 2 schools. The study examined the presence of particulate matter of 1-, 2.5-, and 10-micron diameters (PM1, PM2.5, and PM10), carbon dioxide (CO_2), and sick days reported by staff and students under various operating conditions to determine if PACs could make a statistically significant difference in these IAQ and health indicators. This paper describes the study methods and the following key findings: 1) The indoor CO_2 concentrations were dependent on the presence of occupants and the leaks/openings through the building envelope in the space. Higher CO_2 concentrations were measured in classrooms with higher occupant densities. The CO_2 concentrations measured in both schools agreed with CO_2 concentration metrics predicted based on occupant characteristics and ASHRAE 62.1 ventilation requirements. 2) The outdoor particle sources played the most significant role in deciding the indoor particle concentrations. The presence of exterior walls and windows in a space also affected the indoor particle concentrations. 3) A particle removal efficiency index was defined and used to assess the effectiveness of filtration in removing particles. Based on the PM1 and PM2.5 removal efficiency results, the PAC units in the intervention school were able to remove some of the particles entered indoors.

KEYWORDS

Air cleaning, ventilation, occupancy, particle measurement, CO_2 concentration

1 INTRODUCTION

The NRC's IAQ team has been conducting laboratory and field studies to assess the effectiveness of air cleaning and ventilation in reducing airborne transmission of infectious aerosols and wildfire smoke exposure in buildings. Exhaled aerosols with pathogens are typically smaller than 5 μm, and a large proportion of them are smaller than 1 μm for most respiratory activities such as breathing, talking, and coughing (Fennelly, 2020; Wang et al., 2022). It is widely acknowledged that wildfires generally produce fine (<2.5 μm) and ultrafine particles (<1 μm), which pose the main health risks (Black et al., 2017; ECCC, 2023). In response to the COVID-19 pandemic, there have been many recommendations to monitor indoor CO_2 levels as an indicator of the risk of airborne transmission of pathogens and the adequacy of ventilation rates (CDC, 2021; EMG/SPI-B, 2021; REHVA, 2021).

The aim of this control-intervention study was to determine the effectiveness of deploying portable air cleaners (PACs) for improving indoor air quality and correspondingly, the health of occupants. This was primarily assessed by monitoring the concentration of particulate matter and number of reported sick days by students and staff. Additionally, the CO_2 level was also monitored to indicate whether periods of inadequate ventilation occurred in the two schools.

2 METHODOLOGY

Two schools in the same city with similar characteristics including the year built, heating, ventilation, and air conditioning (HVAC) system, number of rooms (25-30), number of teachers, and number and age of students (kindergarten to Grade 8), were selected for a field monitoring campaign. Phase 1 of the study was from March to June 2023. During this period, the control school relied solely on the existing HVAC system. Meanwhile, the intervention school relied solely on the existing HVAC system in April. After which time, one PAC was used in each classroom and the teachers lounge, and two PACs were used in the library in May and June. Air quality sensors were installed in classrooms, hallways, and other common spaces in both schools to continuously monitor the concentration of particulate matter (PM1, PM 2.5, and PM10), CO_2, temperature, relative humidity, and sound level in both schools. In each of the classrooms, 1 sensor was placed near the door (measurement location A), and another one was placed near an exterior wall/window (if present) or a wall on the opposite side (measurement location B). An outdoor sensor was mounted on the rooftop of each school to monitor these same parameters outdoors.

3 RESULTS AND DISCUSSION

Due to page limitations, the following sections will only display select CO_2 and particle measurements as the major indicators of IAQ.

3.1 Factors affecting indoor CO_2 concentration

Figure 1 shows the outdoor and indoor CO_2 concentrations in two classrooms in the intervention school from the last week of March to June 2023 (14 weeks). The last of week of March (week 1) was spring break. It can be observed from Figure 1 that the indoor CO_2 concentrations were primarily dependent on the presence of occupants. However, the presence of exterior walls and windows also played a role in affecting indoor CO_2 concentrations. For example, classroom INT-C-02 has exterior walls and windows, and sensor B near the windows in this room often recorded lower concentrations than sensor A near the door did. This can be seen more clearly in Figure 2. All the walls in classroom INT-C-10 were interior, and the two sensors in this room generally agreed with each other well. It is worth noting that the details about the HVAC system's operating schedule, the outdoor air intake rate, the in-duct filter efficiency, and the air infiltration through building envelopes were unknown in these classrooms. Additionally, a PAC was installed in both classrooms at the end of week 6 and has been kept on continuously after, which did not affect the CO_2 concentrations in both classrooms, as expected.

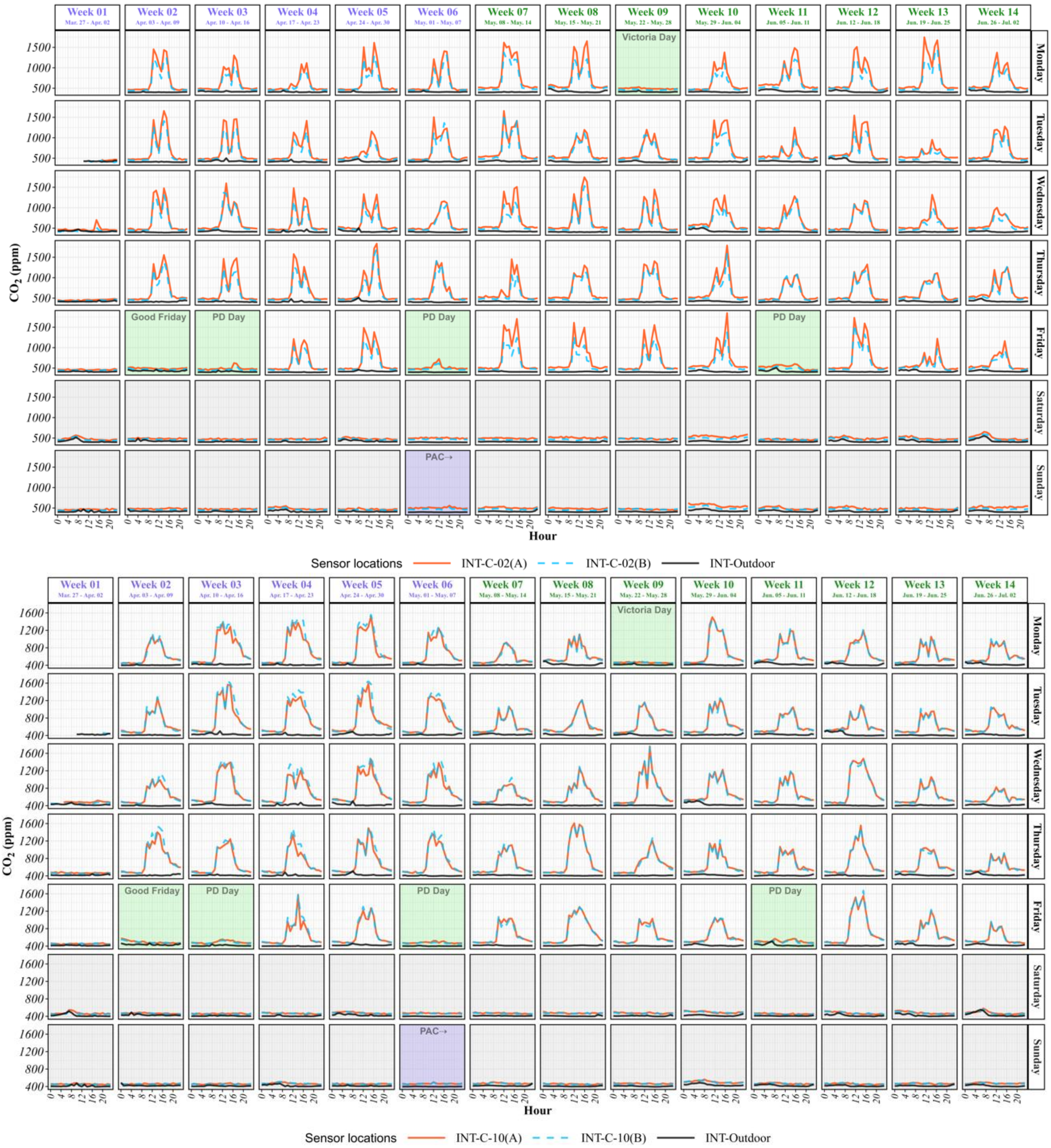


Figure 1: Outdoor and indoor CO_2 concentrations in 2 classrooms in the intervention school: with exterior windows (above) and without (below)

The CO_2 concentrations in two adjacent classrooms, INT-C-02 and INT-C-03, in the intervention school on April 11 and May 16 are plotted in Figure 2. These classrooms have similar layouts, dimensions, and HVAC system configurations. INT-C-02 had 29 students (ages 11 to 12), whereas INT-C-03 had 20 students (ages 13 to 14). The higher occupant density in INT-C-02 resulted in higher CO_2 concentrations than the levels observed in INT-C-03 between 8 AM and 4 PM when the rooms were occupied. The CO_2 concentrations measured from both schools during the occupied periods agreed with the CO_2 concentration metrics proposed by Persily (2022) for classrooms based on occupant characteristics and ASHRAE 62.1 ventilation requirements.

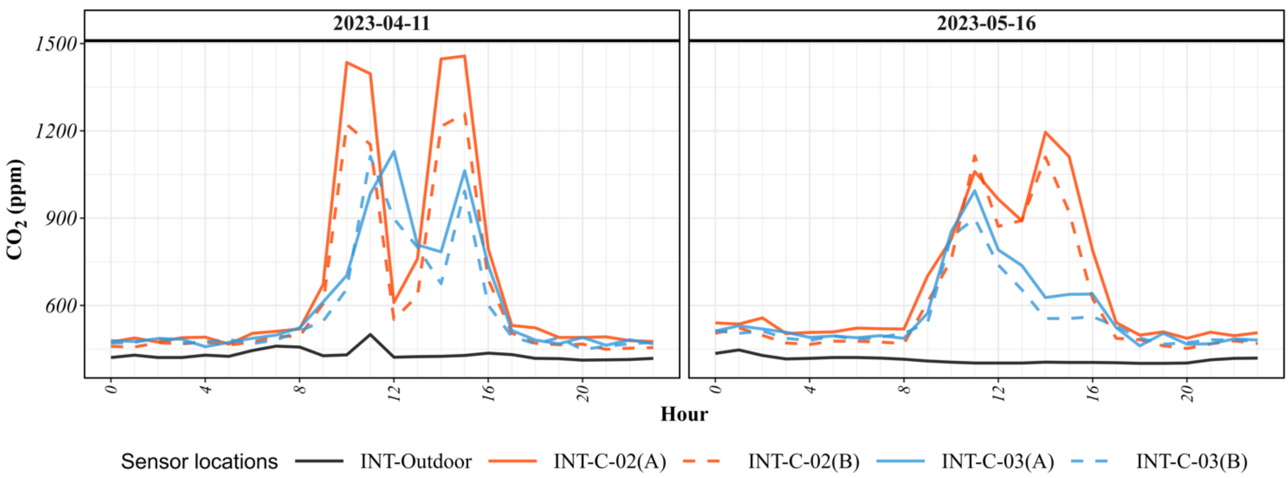


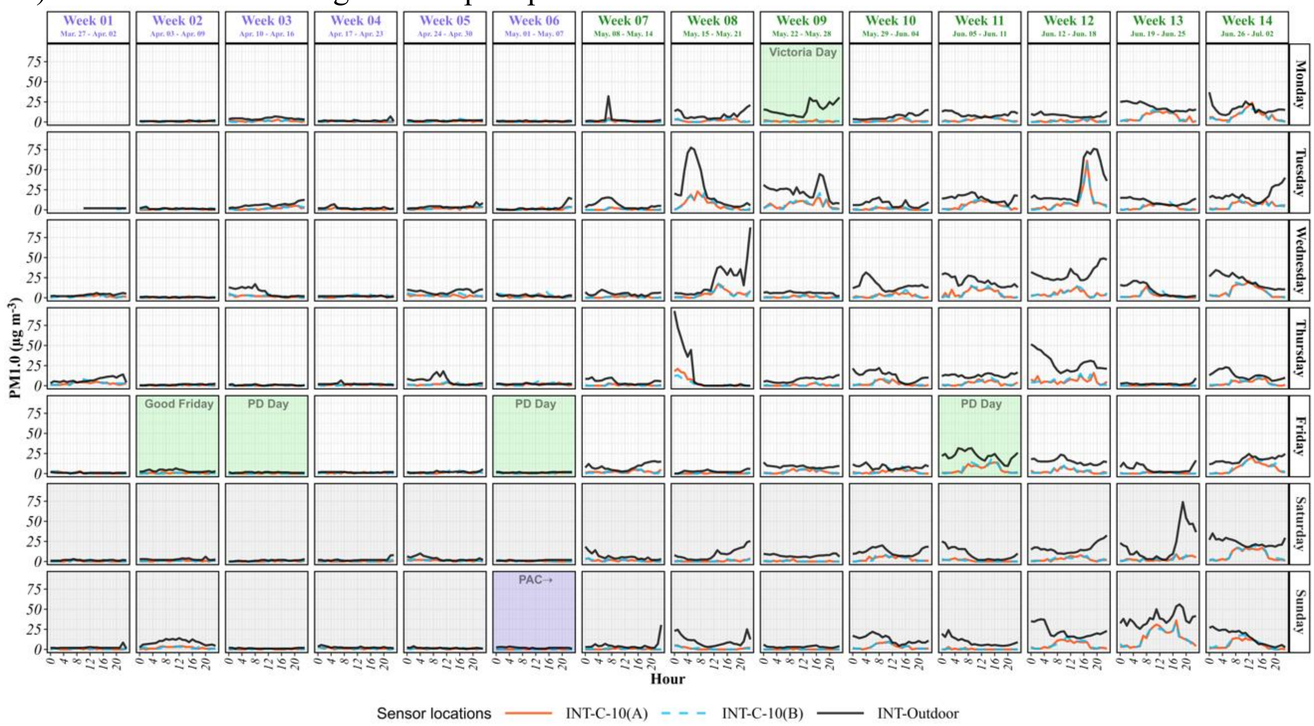
Figure 2: CO_2 concentrations in 2 classrooms in the intervention school on April 11 and May 16

The CO_2 measured on May 16 in both classrooms were lower than the readings on April 11. One possible reason for this is that outdoor air with a lower CO_2 concentration entered the space through open windows and/or the HVAC system when weather became warmer on May 16.

3.2 Factors affecting indoor PM1 and PM2.5 concentration

2.2.1 Outdoor PM1 and PM 2.5 concentration

Figure 3 andFigure 4 present the indoor and outdoor PM1 and PM2.5 concentrations measured in classrooms INT-C-10 and CTL-C-10 during the 14-week testing period from March to June. The results between weeks 7 and 12 in Figure 3 and Figure 4 demonstrate that the outdoor sources played the most significant role in deciding the indoor PM1 and PM2.5 concentrations during this period. The higher than usual outdoor particle concentrations in this period were likely correlated to the wildfire events in a neighbouring province at the same time (2023 Alberta wildfires - Wikipedia). No PAC units were used in either school between week 1 and week 6, and the concentrations of PM1 and PM2.5 in both classrooms (INT-C-10 and CTL-C-10) did not increase during the occupied period between 8 AM and 4 PM.



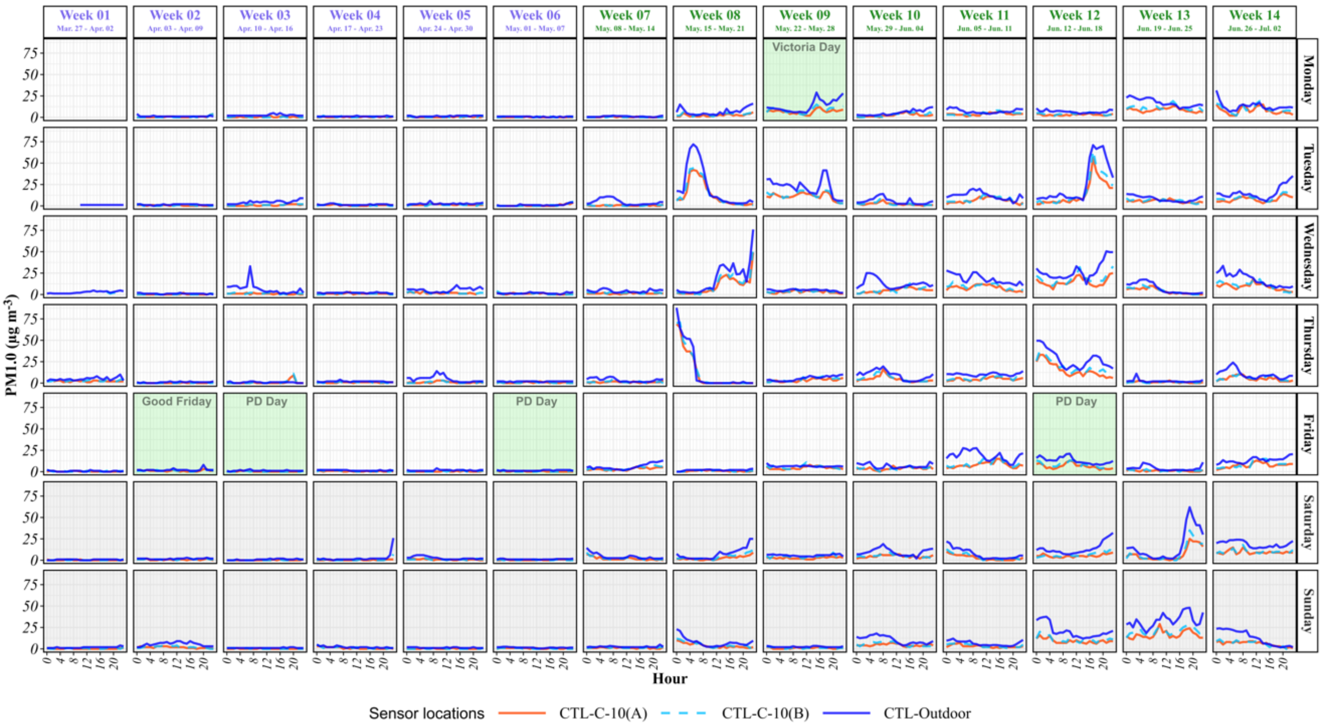
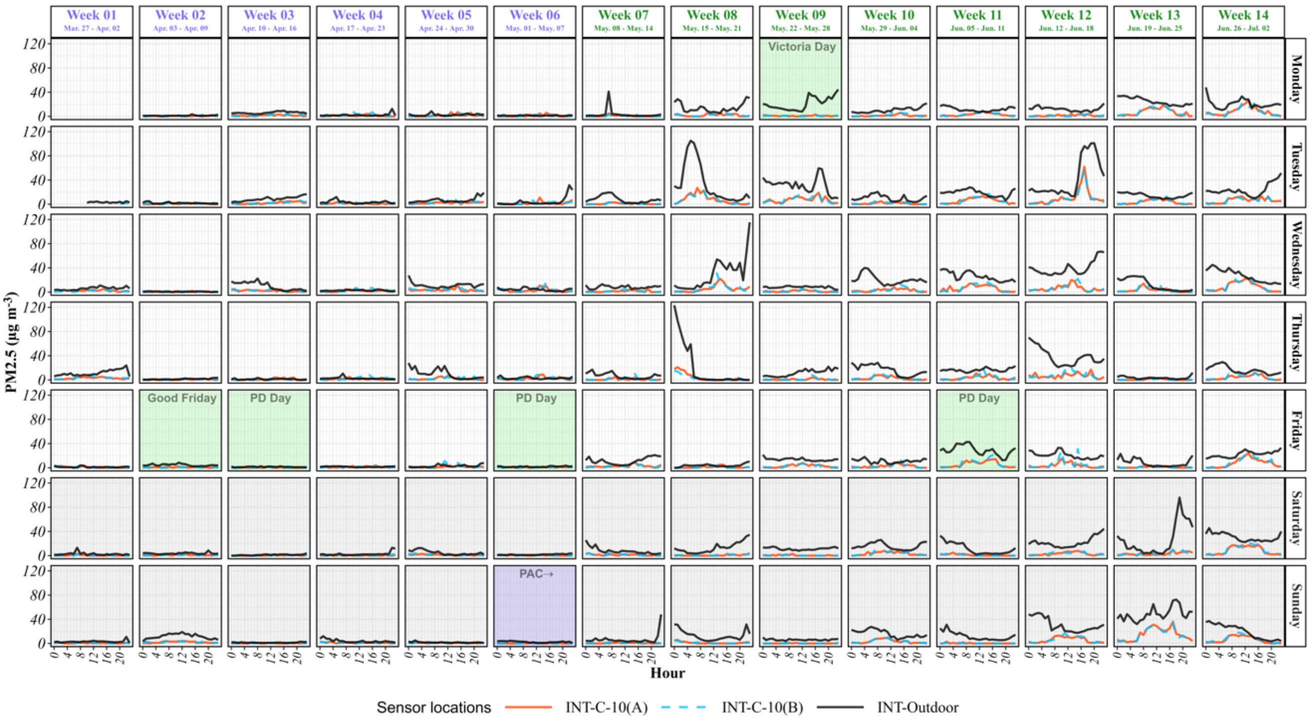


Figure 3: PM1 concentrations: a classroom in the intervention school (above) and in the control school (below)



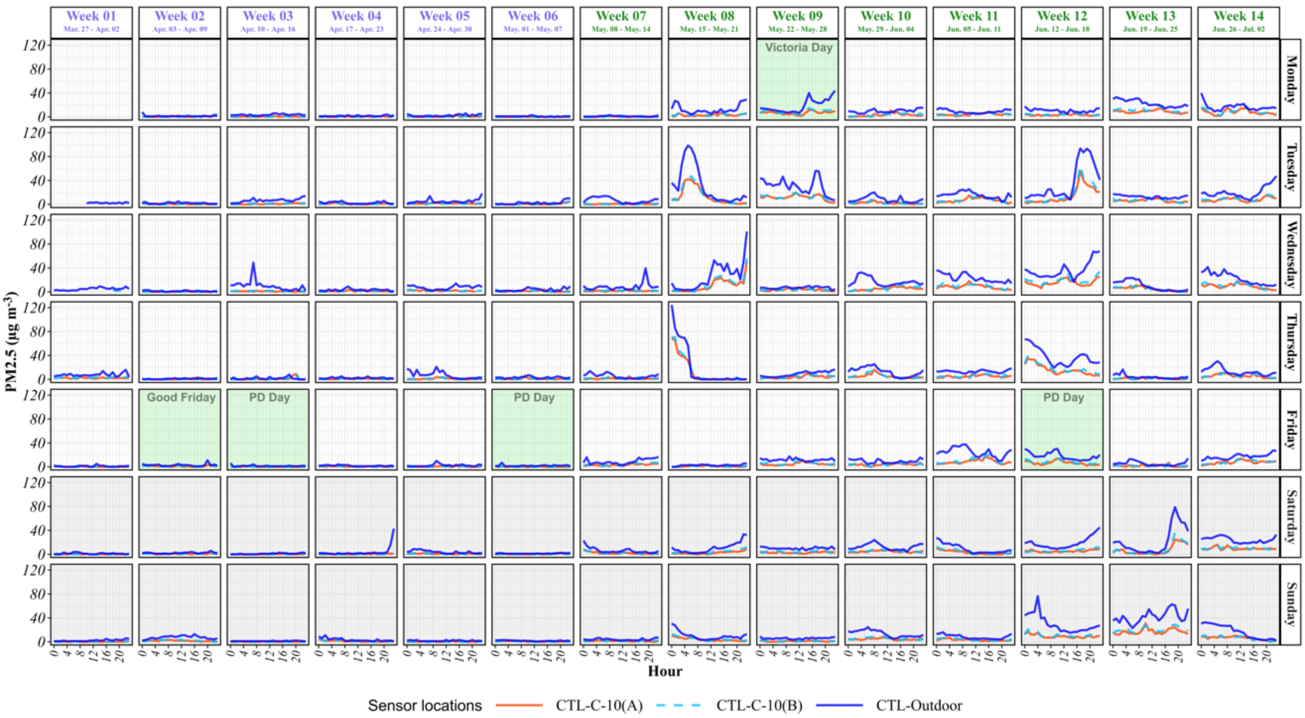


Figure 4: PM2.5 concentrations: a classroom in the intervention school (above) and in the control school (below)

2.2.2 Operation of PACs

The PM1 concentrations in 2 classrooms in the intervention school on April 11 and May 16 are plotted in Figure 5. Classrooms INT-C-09 and INT-C-10 have the same layouts, dimensions, HVAC system configurations. Neither room has exterior walls or windows. The PAC in INT-C-09 was controlled by a timer to operate between 8 AM and 5 PM, whereas the PAC in INT-C-10 was operating continuously. Compared to the PM1 results from INT-C-09, the operation of the PAC between 2 and 8 AM in INT-C-10 significantly reduced the indoor PM1 concentration when the outdoor PM1 levels were high during this period.

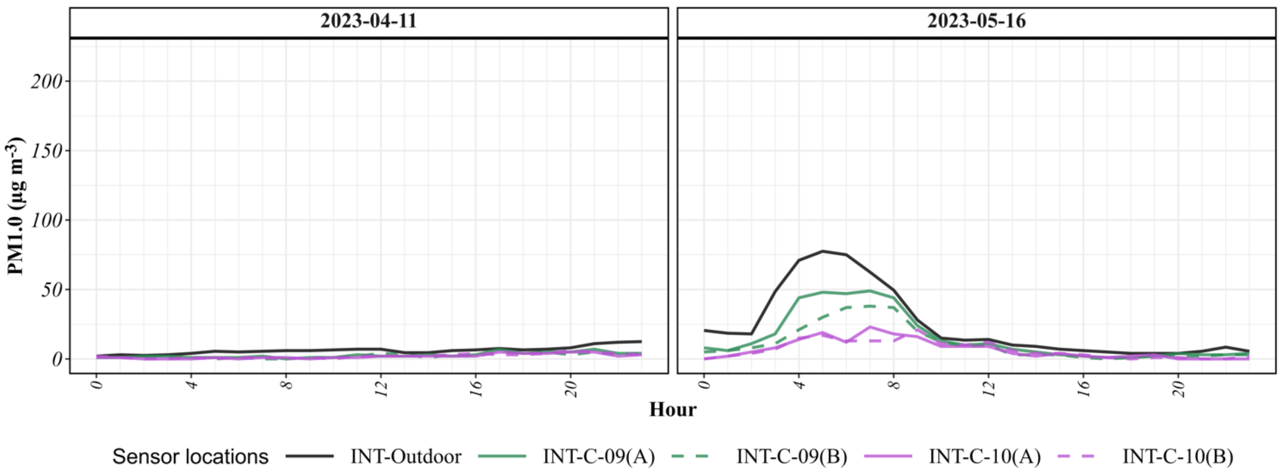


Figure 5: Effect of intermittent operation of PAC and occupancy on indoor PM1

2.2.3 Exterior walls and windows

The PM1 concentrations in two classrooms in the intervention school on April 11 and May 16 are plotted in Figure 6. These two rooms, INT-C-10 and INT-C-15, have the same layouts, dimensions, HVAC system configurations, and PAC operating schedules (continuous). As previously mentioned, INT-C-10 has no exterior walls, whereas INT-C-15 has. It can be seen in Figure 6 that the concentration of PM1 in INT-C-15 was much higher than that in INT-C-10 when the outdoor PM1 concentration was high between 2 and 10 AM on May 16, indicating that PM1 particles likely infiltrated to indoors through the exterior walls and windows in INT-C-15.

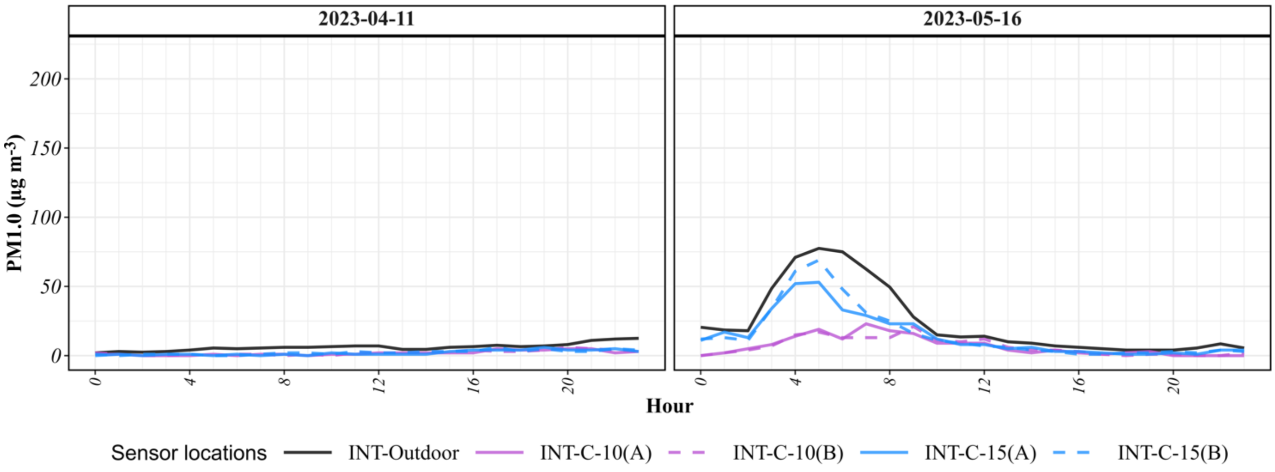


Figure 6: Effect of exterior windows/walls on indoor PM1: INT-C-10 without and INT-C-15 with

2.2.3 Operation of PAC in rooms with exterior walls and windows

The PM1 concentrations in two comparable classrooms in the intervention school on April 11 and May 16 are plotted in Figure 7. As previously mentioned, INT-C-02 and INT-C-03 share similar characteristics, and both have exterior walls and windows. The PAC in INT-C-03 was controlled by a timer to operate between 8 AM and 5 PM, whereas the PAC in INT-C-02 was operating continuously. When the outdoor PM1 concentration was high between 2 and 10 AM on May 16, the concentration of PM1 in INT-C-02 was similar to what was measured in INT-C-03, even the PAC in INT-C-02 was operating. This indicates that the capacity of the PAC unit in INT-C-02 might be insufficient to effectively remove all the PM1 particles that infiltrated through the exterior walls and windows in this room.

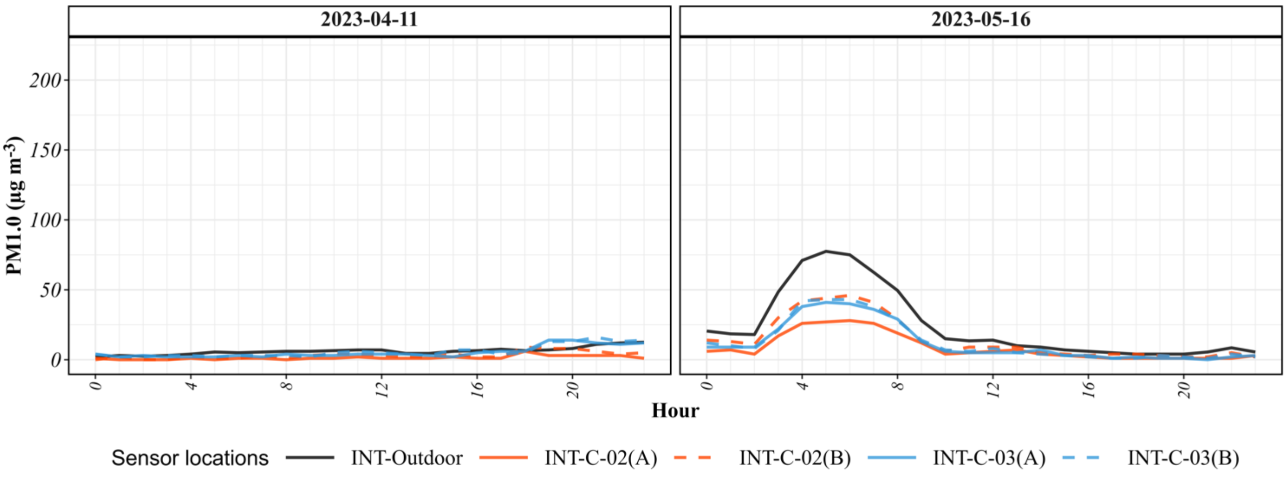


Figure 7: Operating of PAC in rooms with exterior walls and windows

3.3 PAC's ability to reduce indoor PM1 concentration

The test results presented so far demonstrate that the outdoor sources played the most significant role in deciding the indoor PM1 and PM2.5 concentrations in both the control and the intervention schools. During the study period, the outdoor particle concentrations were consistently higher than the indoor particle concentrations. A particle removal efficiency index can be used to assess the effectiveness of filtration in removing particles.

$$PM_{eff} = 1 - \frac{PM_{indoor}}{PM_{outdoor}}$$

In the control school, particles from outdoor sources were removed by the HVAC system in-duct filters and the building envelope. In the intervention school, particles from outdoor sources were removed by the HVAC in-duct filters, the building envelope, and the PAC units with HEPA filters after these units were deployed on May 6, 2023. Particle removal efficiencies were calculated using the time series data collected from both schools on April 11 and May 16. Table 1 presents the average PM1 and PM2.5 concentrations and removal efficiencies calculated based on the data from two classrooms (one with exterior walls/windows and one without) in each school. Wildfire events happened in a neighbouring province in May 2023, which likely contributed to the rise in the outdoor PM1 and PM2.5 concentrations. The PAC units were operating continuously in the two classrooms in the intervention school after they were deployed.

Table 1: PM1 and PM2.5 concentration and removal efficiency

School	**Date**	**PAC (Y/N)**	**Outdoor PM1 conc ($\mu g/m^3$)**	**Indoor PM1 conc ($\mu g/m^3$)**	**Outdoor PM2.5 conc ($\mu g/m^3$)**	**Indoor PM2.5 conc ($\mu g/m^3$)**	**PM1 removal efficiency**	**PM2.5 removal efficiency**
Control	April 11	N	4.53	1.54	6.70	1.70	0.66	0.74
Control	May 16	N	22.07	14.97	32.11	15.55	0.29	0.48
Intervention	April 11	N	6.22	2.16	8.81	2.31	0.65	0.74
Intervention	May 16	Y	24.65	9.26	34.07	9.69	0.61	0.70

Figure 3 and Figure 4 illustrate that the outdoor concentrations of PM1 and PM2.5 on May 16 were much higher than those on April 11. The elevated outdoor particle concentrations on May 16 resulted in much lower PM1 and PM2.5 removal efficiencies than the efficiency achieved on April 11, as seen in Table 1. On April 11, no PAC units were deployed and used in both schools. On May 16, PAC units were used only in the intervention school. Table 1 shows more pronounced decreases in particle (both PM1 and PM2.5) removal efficiencies between these two days in the control school, compared to the intervention school. Based on the considerations of all these factors, the PAC units appeared to remove some of the particles that entered indoors. To quantitatively determine the particle removal efficiency of the PAC units, comparative tests need to be carried out when outdoor particle concentration remains at a reasonably constant level.

In all scenarios, the calculated PM2.5 removal efficiencies are higher than the PM1 removal efficiencies. This is consistent with filter particle size efficiency in ASHRAE 52.2 (ASHRAE, 2017), meaning that a filter is generally more efficient in removing particles in larger size ranges. It is worth noting that the design limit of PM2.5 in ASHRAE 62.1 (ASHRAE, 2022) is 12 $\mu g/m^3$, which is the annual standard for PM2.5 averaged over three years defined by the US Environmental Protection Agency.

4 CONCLUSIONS

From April to June 2023, a control intervention study was carried out in two schools with similar characteristics to determine the effect of deploying PACs with HEPA filters on IAQ and the health of the students and staff. This paper presents the CO_2, PM1, and PM2.5 measurement results under various operating conditions. The details about the HVAC system's operating schedule, the outdoor air intake rate, the in-duct filter efficiency, building envelope airtightness, and the air infiltration through building envelopes were unknown in both the control and intervention classroom. Despite these limitations, the following observations and conclusions can be made.

- The indoor CO_2 concentrations were primarily dependent on the presence of occupants. Higher CO_2 concentrations were measured in classrooms with higher occupant densities. However, the infiltration and exfiltration through building envelope can play a role in affecting indoor CO_2 concentrations and the readings recorded by the indoor CO_2 sensors, depending on where the sensors are located (i.e. the distance between the sensors and the exterior walls and/or windows). The CO_2 concentrations measured from both schools during the occupied periods agreed with the CO_2 concentration metrics proposed by for classrooms Persily (2022) based on occupant characteristics and ASHRAE 62.1 ventilation requirements.
- The outdoor particle sources played the most significant role in deciding the indoor PM1 and PM2.5 concentrations during the study period. The increase in outdoor particle concentrations in May and June were likely correlated to the wildfire events in a neighbouring province. The presence of exterior walls and windows in a space can also affect the indoor particle concentrations because the infiltration and exfiltration though the building envelope allow particles to enter or leave the space.
- During the study period, the outdoor particle concentrations were consistently higher than the indoor particle concentrations. A particle removal efficiency index was used to assess the effectiveness of filtration in removing particles. Based on the PM1 and PM2.5 removal efficiencies calculated for both schools during the testing periods with and without the operation of PAC units in the intervention school, the PAC units in the intervention school were able to remove some of the particles that entered indoors.
- Based on the observations above, CO_2 concentration can be used to control ventilation for using outdoor air to dilute indoor air contaminants, particularly those generated by occupants, whereas outdoor and indoor particle measurements can be used to determine the needs for ventilation, filtration, and air cleaning. If CO_2 and particle readings are to be used for the control of ventilation and air cleaning, the number and the location of the sensors require careful consideration. Moreover, further research is required to better understand how particle measurements can be used to control ventilation and air cleaning systems.

In the next phase of the study, efforts will be made to examine the building envelope airtightness, HVAC system's operating schedule, ventilation rate (e.g. CO_2 decay after occupancy or other tracer gas methods), PAC airflow rates, in-duct filter efficiency, PAC filter efficiency, and sick days reported in both schools. The goal is to verify the cost and effectiveness of air cleaning and ventilation measures on IAQ and occupants' health in public spaces with shared indoor air.

5 ACKNOWLEDGMENTS

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