Post-Occupancy study of indoor air quality in university laboratories during the pandemic

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SUMMARY
This post-occupancy study aims to assess the indoor air quality (IAQ) and ventilation performance in workshops and laboratories of a UK university during the COVID-19 pandemic. Supply airflow rates and CO_2 were monitored as a proxy for evaluating ventilation performance. Additionally, particulate matter (PM_{10}) was monitored to address the occupant's concerns about dust. Monitoring showed that maximum CO_2 values recorded are mostly below 1000 ppm, with weekly averages below 520 ppm. This was expected as the supply airflow rates were significantly larger than recommended 10 l/s per occupant. Despite the large flow rates, PM_{10} levels in some laboratories were above the threshold value of 50 [μg/m^3] supporting the poor IAQ claims of the occupants. The study indicated the room air re-circulation and indoor activities as the likely reasons for the elevated PM_{10} levels and some practical operational solutions were suggested for IAQ concerns.

KEYWORDS
Indoor Air Quality (IAQ), CO_2, PM_{10}, Ventilation, SARS-CoV-2

1 INTRODUCTION

For students and staff throughout UK universities, the impact of the COVID-19 pandemic on daily working and studying life has been profound. While lectures and seminars tend to translate well to online learning, practical experiments and exercises led in laboratories and workshops, with unique access to specialised equipment and technicians, cannot be replicated.

Following initial hesitancy, aerosol or, “inhalation” transmission is now widely accepted as a significant mechanism of transmission of Covid. Due to their small size and mass, aerosols smaller than 50 µm can stay suspended in indoor air for hours, their concentrations rising in enclosed environments where people gather for prolonged periods, and where ventilation is insufficient for the number of people using the space. However, direct monitoring of virus-containing aerosol is impracticable. Providing sufficient outdoor air through ventilation strategies has been identified as a mitigation measure that can significantly reduce the risk of airborne transmission in indoor spaces for SARS-CoV-2 and it is unquestionably an important strategy in infection control, pointing to the need to ensure good ventilation performance, as in any occupational setting the possible number of infectors is unknown and so is are the concentrations of the virus in the air (Dai & Zhao, 2020, and Di Gilio et al., 2021, to name a few). Indoor CO_2 concentrations have been routinely used as a practical proxy for airborne transmission of infectious diseases, as pathogen-containing aerosols and CO_2 are co-exhaled by those infected (Peng and Jimenez, 2021), and both concentrations build up in the space, although there is no direct correlation between the two (Jones et al., 2021). In addition, background CO_2 concentrations are usually stable, and indoors, excess CO_2 above background levels derive almost exclusively from human exhalation. Hence, monitoring of transient indoor CO_2 and Indoor Air Quality (IAQ) by cost-effective sensors can indicate if an indoor space has sufficient ventilation and whether there is a risk of build-up of the virus in the air which would require intervention.

The UK Scientific Advisory Group for Emergencies-Environmental Modelling Group (SAGE-EMG) and the UK Independent Scientific Pandemic Insights Group on Behaviours (SPI-B) have recommended to the UK government that there be enhanced ventilation and CO2 monitoring during the pandemic and made a series of recommendations for target CO_2 values; these targets were also adopted by the Chartered Institute for Building Service Engineers (CIBSE) and have been used to inform numerous operational strategies and research projects in the UK between 2020 – 2022. Though enhanced ventilation to ensure target CO_2 values below 800 ppm was recommended, the pragmatic target for interventions was to prioritise spaces regularly presenting values above 1500 ppm as being the most urgent to address.

Following pandemic guidance, University College London (UCL) implemented changes to ventilation system operations across the estate, to stop room air re-circulation and to introduce 100% outdoor air into all mechanically ventilated (MV) spaces, in order to reduce the risk of airborne transmission of SARS-CoV-2. The objectives of this study are to investigate the performance of seven laboratories and one workshop at the department of CEGE, UCL, with regard to indoor air quality following the recent implementation of operational changes to the ventilation systems by UCL. Performance is assessed by monitoring airflow rates and CO_2 concentrations and comparing them to UK national COVID-19 mitigation guidelines, and evaluating whether the occupancy of the labs is appropriate for the ventilation provided.

Some of the lab employees spend the majority of their time indoors, in the laboratory, and concerns were raised about the increased risk of respiratory diseases (e.g. asthma and allergies) and cardiovascular diseases associated with elevated concentrations of particulate matter (Sicard et al., 2019). Therefore, the study further aims to evaluate IAQ in the labs and workshop in terms of particulate matter, as the occupants of these laboratories believed that since the changes to the ventilation system operations were made, the labs had become dustier and that dust was possibly being delivered to the labs via the ventilation system. Following a measurement survey, particulate matter concentrations in the labs are compared against the UK Air Quality Strategy (AQS) PM_{10} guidelines, where hourly and annually guidelines for workspaces are, respectively, 50 and 40 µg/m³ for PM10 (British Safety Council, 2022).

2 METHODS

Ventilation rates, indoor and outdoor air quality and occupancy were assessed in this study in seven laboratory spaces and one workshop. The laboratories are located on three levels. Basement laboratories include the Environmental, Materials, Soil, Fluids laboratories and the Workshop as shown in Figure 1. The Fluids Laboratory is naturally ventilated (NV) and other listed spaces in the basement have MV. The Fluids laboratory does not have any windows and the ventilation is provided through an exterior door at the back of the room, which is kept open when there are occupants. Ground-level labs include the Advanced Structures Lab which is MV, and the G04 open teaching space which is NV only through infiltration or occasional people movement through the fire doors on both ends. The HIRG lab is located on level 2 and is MV.

Duomo Senseair Explora CO_2, wireless, battery-powered sensors that monitored the concentrations of CO_2, temperature, and relative humidity of the laboratories continuously were installed in all stated spaces. The CO_2 sampling method was non-dispersive infrared (NDIR), capable of measuring within a range of 400–5000ppm at an accuracy of ±30ppm (±3% of reading). At a sampling interval of 2 minutes, the data logged was then securely transmitted wirelessly to the cloud (EMG, 2021). To investigate the ventilation system in further detail, sensors were attached to the supply air terminal grills and compared with indoor CO_2 in the rest of the space, as indicated in Figure 1, which shows a schematic of all the laboratories (a), and position of sensors in the Soils lab (b), with those that were positioned near the supply inlets marked in blue.

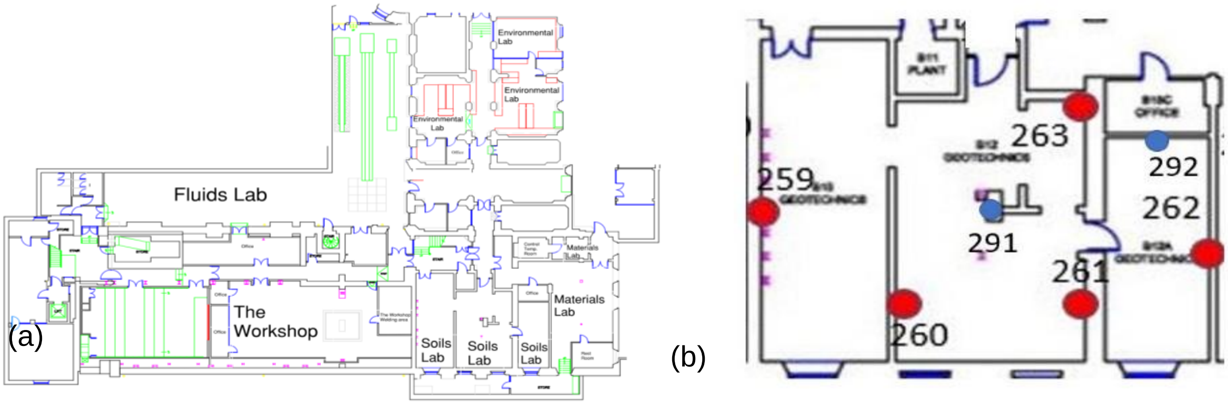


Figure 1: (a)Basement laboratories and the workshop layout; (b) Sensor positions in the Soils Lab; red circles indicate sensors for ambient air quality, and blue circles - sensors for supply air

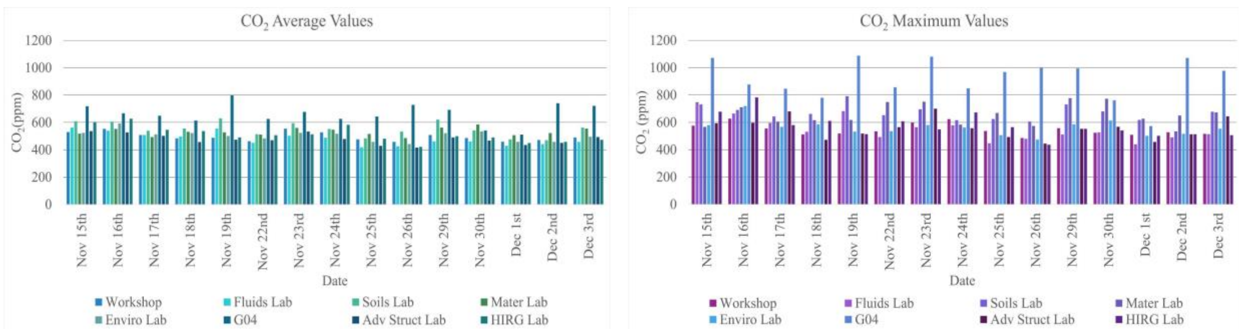
Particulate matter of size less than 10 μm (PM_{10}) was logged in six laboratory spaces over three weeks using two monitors. Every week, two spaces were monitored at a time, after which the instruments were moved to the next set of laboratories. TSI aerosol monitors, DustTrak II 8532 and SidePak AM520, which are photometric devices, were used in this study due to their ease of use and their ability to provide results in real-time. Several studies show that photometric and gravimetric studies are comparable. A study (Language et al. 2016) comparing gravimetric and photometric methods, found a strong correlation between the two methods, with a correlation coefficient of 0.79 for DustTrak and 0.64 for SidePack. Before the study began, the devices were tested in the same room for 10 minutes to compare their baseline readings with each other and the average difference between the two device readings was 0.001 mg/m^3. The logging interval was 5 seconds, and the resolution of both devices is 0.001 mg/m^3.
Monitoring outdoor dust directly was not possible within this study, but there were no identified activities (such as construction) occurring around the labs or the supply inlets to the labs at the time of the study. In order to understand whether indoor dust is likely to be from outdoor pollutant sources, outdoor PM_{10} data was obtained from the IQAir (2022) and Air Quality in England (2022) websites, which report data captured by fixed roadside monitoring stations that belong to the UK Automatic Urban and Rural Network (AURN). The Euston Road station and Bloomsbury station were selected: the vertical distance from these stations to the building housing the laboratories at UCL are within 500m and 150m respectively, and averages of both datasets were used.
Occupancy in all laboratory spaces except G04 was logged on attendance forms that were filled out by staff and students when entering and exiting the laboratory. Occupancy was monitored for three weeks, after which all forms were collected, and the number of people present in the space was analysed. It should be noted that due to the preference for working from home and blended learning in the UK at the time, the occupancy was reduced from pre-pandemic numbers at the time of this study in all spaces.
The ventilation flow rates were measured by the Environmental Monitor EVM-7 (TSI), which was fitted with a hand-held anemometer AirProbe 10. The airspeed measurements were taken at several locations (>10 measurement points) on each ventilation supply terminal and then the average airspeed was multiplied by the area of the supply terminal (Equation 1). The sampling frequency of the airspeed measurement was one second and the measurement continued until a steady value was obtained in each measurement location. The sensitivity of the device is 0.1 m/s.

$$q = v \times A \qquad (1)$$

Where q is the ventilation flow rate [m^3/s], A is the area of the supply terminal [m^2], and v is the average speed of the air passing through the supply terminal [m/s].

3 RESULTS

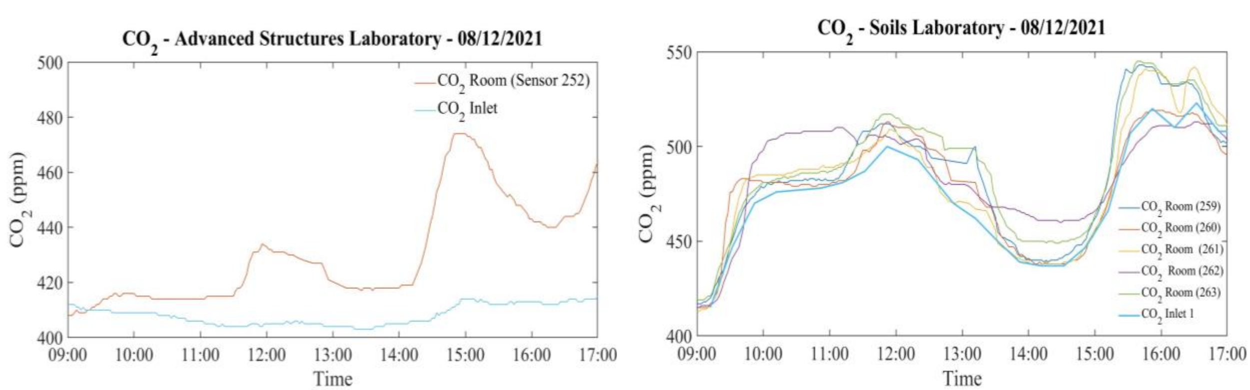
Readings of CO_2 in all laboratories were analysed for the lab occupancy times, from 9 AM to 5 PM on weekdays. CO_2 daily averages were calculated, and daily maximum values were recorded, over the course of three weeks for all spaces. Over the three-week monitoring period, it was found that CO_2 averages were mostly always in the range of 500 to 600 ppm, with only the G04 space having higher average concentrations of up to 800 ppm. This was expected, as G04 is open to all students to use freely for studying and socialising and hence occupancy times are longer, and numbers of occupants can be higher than in the labs; furthermore, G04 does not have a ventilation strategy. Maximum CO_2 values, shown in Figure 2 (b), present worst case values of up to 800 ppm for a majority of the laboratories, with the G04 space reaching just above 1000 ppm.



(a) (b)

Figure 2: (a) CO_2 Average daily values (b) CO_2 Maximum recorded daily

The supply air and room CO_2 values were measured to determine if the ventilation system operates in line with the UK COVID-19 ventilation guidance and supplies 100% outdoor air (CIBSE, 2021). In the absence of room air circulation, the measured supply air CO_2 values are expected to be around outdoor CO_2 values (i.e., around 420 ppm in central London) and to remain steady during the time measurements are taken. In the Advanced Structures Laboratory, the measured supply air CO_2 values were around 410 ppm and remained quite steady (Figure 3 (a)). The situation was different in the Soils Laboratory, where supply CO_2 values were higher throughout, and closely followed the trends in the CO_2 value in the room, indicating the supplied air in the Soils lab was at least partly recirculated; a typical day's CO_2 profile is shown in Figure 3 (b). "Inlet" data represents CO_2 data averaged from the two sensors that were installed near supply grills, as in Figure 1 (b).



(a) (b)

Figure 3: The comparison of the supply air and room CO_2 values for (a) Advanced Structures Laboratory; (b) Soils Laboratory

The measured ventilation flow rates were used to determine the acceptable occupant density in these spaces based on a suggested ventilation flow rate of 10 l/s per person (CIBSE, 2021) and assuming that they are made up of 100% as the data suggested. Assuming that the ventilation efficiency is acceptable (i.e., the spaces are well mixed) and there is no room air circulation, then based on the recommended flow rates, 16, 112, 103 and 24 people could be accommodated in the Materials and Environmental Laboratories, Workshop and HIRG facility respectively (Figure 4). Ventilation flow rates in the fluids laboratory and G04, both (NV) were not established as these had varying occupancy and no ventilation strategy. The 10 l/s per person flow rate guidance applies to spaces that have no room air re-circulation, thus total flow rate was not analysed in the Soils lab where re-circulating air was shown, as this would not be indicative of outdoor supply.

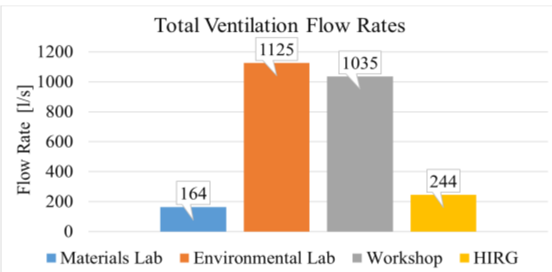


Figure 4: Total ventilation flow rates for mechanically ventilated spaces, in l/s

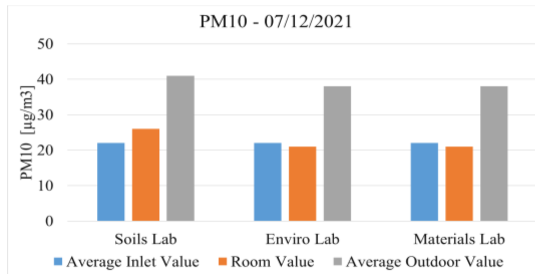
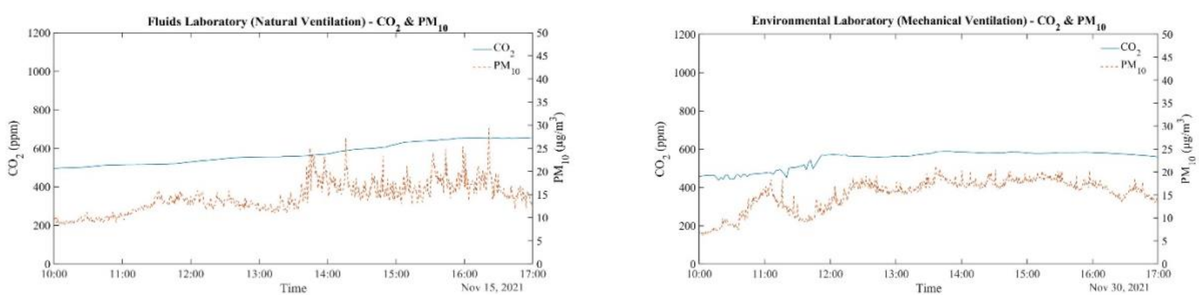


Figure 5: PM_{10} at ventilation supply terminal, in the room and outdoors

PM_{10} values measured simultaneously at the ventilation supply terminals and indoor spaces were compared with background outdoor values reported by the AURN to investigate how effective the ventilation system was in filtering out the outdoor PM_{10} and attempt to determine whether it was likely that dust was being brought into the labs via the ventilation system as the occupants believed. These measurements were carried out for half a day on the 7th of December 2021, after the rest of the measurements had been completed. Figure 5 shows that indoor PM_{10} levels are significantly lower than outdoor levels in all three labs.



(a) (b)

Figure 6: (a) Fluids Laboratory (NV); (b) Environmental Laboratory (MV)

Two laboratories, one NV and the other MV are compared in terms of CO_2 and PM_{10} measurements. The days with the highest occupancy were chosen for this analysis. In the Fluids lab, which is NV, the maximum number of occupants was recorded on the 15th of November from 2 to 5 PM when 7 individuals were present to observe a laboratory demonstration. Up until 2, only one person was in the laboratory continuously. Figure 6 (a) shows a slight increase in CO_2 readings

that starts at 2 PM and never exceeds 600 ppm and spikes in PM_{10} that never exceed 30 μg/m^3. Figure 6 (b) shows measurements from the Environmental laboratory, which is MV, on the 30th of November. Three people were in the laboratory from 10 AM – 5 PM, two additional people were present in the morning from 10 AM to 1 PM, resulting in the lab's maximum recorded occupancy of 5 people in total. One additional person was in the laboratory from 2 to 4 PM, resulting in occupancy of 4. Figure 6(b) depicts constant CO_2 values of about 500 ppm, and some PM_{10} spikes at times of higher occupancy that do not exceed 20 μg/m^3.
Daily averages of PM_{10} data collected in the labs over three weeks are presented in Table 1. The PM_{10} data were only averaged over 10 AM to 5 PM during weekdays and weekends, to observe the effects of occupancy. Average outdoor levels from the two nearby AURN monitoring stations are also shown in Table 1. The results show that most laboratories have lower average PM_{10} values over the weekends. The Soils laboratory presents with constantly high readings throughout the week, including on weekends, and the workshop presented elevated values on weekdays only. The values in the Materials laboratory were above the UK hourly limit only on one day of monitoring.

Table 1: Indoor and outdoor average PM_{10}. Week 1:13 - 19/11/2021; Week 2: 20 - 26/11/2021; Week 3:27/11 - 03/12/2021; Colour code for table: Green – up to 35μg/m^3, Yellow - 35 - 40 μg/m^3, Red – Over 40 μg/m^3

Week	Outdoor/ Laboratory	Saturday	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday
1	Workshop	10	11	58	105	46	60	68
1	Fluids	1	7	14	29	10	10	8
1	Outdoor	11	17	25	26	23	19	14
2	Adv.Struc	4	2	3	13	22	2	1
2	Soils	58	48	53	73	82	79	53
2	Outdoor	13	14	21	32	37	18	16
3	Materials	9	11	70	40	19	18	35
3	Enviro	3	3	22	15	5	6	8
3	Outdoor	14	14	38	71	19	17	21

4 DISCUSSION

Ventilation flow rates, CO_2, and PM_{10} measurements were used to assess ventilation performance and IAQ in monitored spaces. In particular, the CO_2 data was used to investigate if the supplied air in MV spaces consisted of 100 % outdoor air. The average and maximum CO_2 indicated that the ventilation was adequate for removing the exhaled air for the reduced occupancy operations that are currently in place. The study found that average and maximum CO_2 levels recorded were mostly below 800 ppm, meaning sufficient outdoor air was being supplied to all the spaces for the occupancies. The G04 space had slightly elevated CO_2 levels, as a space with no ventilation strategy and no control for occupancy, this was expected. Despite this, the maximum recorded values in G04 were still within the SAGE-EMG recommended guidelines for mitigation against transmission of SARS-CoV-2 at the time. The study demonstrates that for the occupant numbers at the time, ventilation rates were sufficient and the mitigations applied by the university had been successful. The results are not indicative of what may happen when occupancy patterns return to pre-pandemic levels, although safety requirements would always have limited the numbers of occupants in these labs.
The supply air and room CO_2 measurements indicated that in one space, the Soils Laboratory, the supply air CO_2 was only very slightly lower than the indoor values. Moreover, the trend of supply and indoor air CO_2 measurements in the Soils Laboratory were similar, indicating that part of the supplied air consisted of re-circulated room air. On the other hand, in all other spaces (e.g., Advanced Structures Laboratory), the supply air CO_2 values were steady and similar to outdoor

values, suggesting that the supplied air was outdoor air without room air re-circulation. These indicated that the mitigations for ventilation systems were applied correctly in all spaces but one.

The measured total flow rates in the MV laboratories that were supplied via outdoor air were found to be up to an order of magnitude higher than the suggested guidance, for the occupancies observed: the Materials and Environmental labs, the Workshop and HIRG. These laboratory spaces may have been overventilated. Over ventilating can lead to thermal discomfort, especially during the winter months when this study was conducted, and to a substantial waste of energy.

Air flows were not monitored in NV Fluid's lab and G04 due to the limitations of identifying where air ingress occurred and the transient occupancy of the G04 space. This means that CO_2 levels might be higher when occupancy is increased in future but this may not be of concern when the risk of transmission is lower. The CO2 measurements showed that the current natural ventilation strategy through the open door in the Fluids Lab produces sufficient outdoor air ingress for 7 occupants. Further research is necessary to determine, under different weather conditions, how many occupants can be in the Fluids Lab safely in future, in terms of air quality.

Detailed information about the filters used on site, or of the design flow rates, was not available for this study and in our experience of field studies, this kind of information is often unknown by building maintenance staff. However, the short term simultaneous PM_{10} measurements were taken at the ventilation supply terminals and indoor air of the laboratories and these were compared with outdoor levels for three MV basement labs in Figure 5. Simultaneous measurements at the supply terminal and in the indoor spaces were lower than outdoor values and demonstrated that the ventilation system seemed to be effective at filtering at least 50% of the outdoor PM_{10} values.

Apart from the Workshop, Soils laboratory and Materials laboratory, other monitored spaces had average PM_{10} levels below the UK AQS hourly guidelines. PM_{10} spikes corresponded to occupant numbers in both MV laboratories, despite low values at the inlet supplies, indicating that, dust particles were most likely suspended in the air because of human activity. The Environmental Lab had the lowest levels of PM_{10} and was also the only lab to utilise an air cleaner device; further research would be needed to evaluate the performance of the air cleaner. The workshop had high PM_{10} readings on weekdays, and on the weekends when this room was unoccupied, measurements were lower and within the guidelines. This again indicates that workshop particulate matter comes from work-related activities. The soils laboratory was noteworthy for having had elevated PM_{10} concentrations both during the week and on weekends, and was the only space where re-circulating air was identified. In this lab, the ventilation system is kept on during the weekends to maintain a constant room temperature. Hence, the elevated PM_{10} levels on the weekends and weekdays may be related to the re-suspension of particles generated by activities in the lab. The elevated PM_{10} values observed on one day in the Materials laboratory are likely to be due to the nature of the work involving a range of dusty materials being used in this lab.

5 CONCLUSIONS

Lessons learned from this study can be applied to other indoor laboratories and university spaces. The CO_2 monitoring showed that most of the laboratories and the workshop were compliant with ventilation guidelines for mitigation of airborne disease transmission, and simultaneous measurements of PM_{10} concluded that the ventilation system was effective at filtering outdoor PM_{10} values in all labs but one. Despite this, the indoor PM_{10} values were above the standards in some laboratories and the occupants experienced discomfort and were concerned about an environment they perceived to be dusty. Elevated indoor values can be explained by indoor activity or room air recirculation and it is recommended that some mitigations are considered to reduce the PM_{10} concentrations or reduce exposure to them, where applicable: for example, wearing a dust mask is recommended in the Materials laboratory and in the Workshop when dust-generating work is taking place. Regular and frequent cleaning of surfaces in the Workshop, Materials and Soils lab is recommended, as work done in these spaces often generates dust, and the ventilation system may be enabling re-suspension of PM_{10}. The study highlights the risk of over-ventilating, which might be leading to poor thermal comfort and high energy costs. This study demonstrates that it would be useful to install CO_2 demand-controlled ventilation systems in the laboratories, which have varying occupancy throughout the day, to conserve energy yet ensure good IAQ. The study demonstrates how a short IAQ survey of a number of indoor spaces can yield useful insights on operations and reassurance on most spaces during a pandemic, whilst also identifying specific areas of concern that may need further investigation by building ventilation experts. At a time of limited resources, a fast and pragmatic approach to monitoring can yield useful results.

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