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Evaluating the impact of air purifiers and window operation upon indoor air quality - UK nurseries during Covid-19

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ABSTRACT

Many indoor air pollutants have been demonstrated to have a negative impact on occupants and due to physiological and behavioural differences, young children are more vulnerable to these effects than adults. Millions of children in the UK spend large parts of the day in nurseries, where occupant density is high, and indoor air quality can be poor. Therefore, it is imperative to understand the quality of indoor air in nurseries and how to improve it. The aims of the research presented here were to explore the indoor air quality (IAQ) in nurseries and the impact of both the use of air purifiers and window operations on IAQ. Three nurseries in London were selected and monitored via both continuous air quality sensors and passive sampling covering a total of 21 pollutants. Key findings include that mean reduction rate of $PM_{2.5}$ by using air purifier was 63% with window closed, and 46% with window open. The results also highlight the impacts of operational changes implemented during the Covid-19 pandemic. Windows were operated more frequently for ventilation needs rather than being driven by temperature alone. The increased ventilation in the monitored nurseries in London led to low levels of VOCs and aldehydes (except for formaldehyde and 2-ethylhexanol) but could bring thermal discomfort to occupants. Both temperature and noise levels were shown to be relevant factors impacting the operation of air purifiers. Air purifiers can be effective at reducing $PM_{2.5}$ when combined with proper window operation and have potential to bring substantial health benefits.

1. Introduction

Nursery, also called kindergarten, day-care, or preschool, offers children from six weeks to six years old daily care and early education before they attend elementary school. Outside of the home, schools are where children spend most of their time [1]. There are around 1.2 million 3 and 4-year-olds registered for 15-h entitlement (government-funded early years provision) in UK nurseries (national statistics, UK). It is important to understand the air quality in schools and explore methods to improve it, as poor indoor air quality has negative effects on human health and performance related to respiratory illnesses, allergies, asthma and sick building syndrome symptoms (SBS) [2]. As the immune and respiratory systems of children are not fully developed, nursery children are more vulnerable to the negative impacts of indoor air pollutants than adults [3]. However, studies about indoor air quality in nurseries are scarce [4,5], and indoor air quality in nurseries is not consistent with primary or secondary schools [6,7]. Many of the relevant studies in nurseries focused solely on 2 to 3 pollutants which may not reveal the full picture of indoor air quality and links to building design and operation. A wider range of pollutants should be studied to contribute to the improvement of the indoor environment [8].

Under the study conditions, occupant behaviour was affected by the Covid-19 response measures [9]. In many countries, schools were temporarily closed in 2020 and early 2021 to control the spread of Covid-19 [10]. As schools reopened, proper actions to help control airborne transmission of Covid-19 were needed, especially in naturally ventilated schools where occupants play a critical role in ventilation provision [11]. It should be noted that in addition to diluting some indoor pollutants (e.g., CO_2, TVOCs), opening windows can also result in increases in pollutants from outdoor sources (e.g., NO_2, $PM_{2.5}$) [12,13]. Opening windows also affects the thermal comfort of occupants. It is, therefore, important to understand the drivers of window operation and the impact on IAQ. For schools, studies reported that window operation is mainly related to temperature [14–16]. In the context of the pandemic, it remains important to understand behaviour changes, drivers of window opening behaviour and the impact upon IAQ [9].

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In nurseries, $PM_{2.5}$ could be high and often exceeds the recommended level [4]. Air purifiers can be used to improve air quality in many environments (homes, offices, schools and cars), with purifiers equipped with HEPA (high efficiency particulate air) filters recommended due to their high particulate matter removal efficiency and lack of harmful by-products [17]. Room size, CADR (clean air delivery rate), and location of the air purifier in the building are considered as factors that affect air purifier performance [18,19]. The operational hours of air purifiers are another crucial factor that influences their performance [20]. The reduction of PMs using purifiers with HEPA filters can be as much as 75% in homes [17,21,22]. However, studies concerning the implications of air purifier use in nurseries are limited, and the reported efficiencies of air purifiers in nursery settings varied from 24% to 86% for $PM_{2.5}$ [23–25]. Studies with long term duration, standardised filtration and intervention duration are needed [26]. Additionally, window operation was rarely mentioned in previous studies focusing on air purifiers, but higher air change rates may impact their performance. As window operation can influence IAQ [16], it's important to take the relationship between window and air purifier operation into consideration when studying the effects of air purifiers and the overall benefits to indoor air quality considering a wide range of pollutants.

The aims of the research presented here were to:

- Explore IAQ of UK nurseries during Covid-19 period.
- Understand window and air purifier operation behaviour during Covid-19 period.
- Identify the impact of air purifiers and window operations on IAQ.

2. Methods

2.1. Context

In May 2018, the Mayor's Nurseries Air Quality Audits was launched to help improve the indoor air quality in nurseries in London. Supported by the Greater London Authority (GLA), a trial that aimed to test the effectiveness of air purifiers at reducing indoor air pollution was conducted by WSP Global Inc. in 2019 [27]. The work presented here was carried out as an extension of GLA's nursery study, with a longer monitoring period, additional monitored pollutants, and the same air purifier equipment operated with similar efficiency.

Based on the estimated ambient annual NO_2, PM_{10} and $PM_{2.5}$ concentrations reported by London Atmospheric Emissions Inventory, as well as other relevant datasets published by GLA, 15 nurseries in London with high exposure risks were contacted and 3 of them agreed to participant this study. All selected nurseries are located at urban sites in two boroughs of London, one in Haringey (north London), two in Southwark (south London). Site 1 is close to a heavily trafficked road, and next to the car park of a police station. Site 2 is located in a residential neighbourhood with less traffic. Site 3 is next to two heavily trafficked roads with a nearby garage and a tyre shop (both have frequent kerb side activities). Indoor and outdoor concentration data of temperature, relative humidity, CO_2, CO, TVOCs, PM_{10}, $PM_{2.5}$ and PM_1 data was collected consistently for a 9–11month period using direct-reading instrument methods, data were collected at 5 min intervals and sent/stored to an online server. Passive sampling was also used for monitoring NO_2, O_3, targeted VOCs and aldehydes (section 2.2). Supplementary measurements of window status (section 2.3) and purifier operation (section 2.4) were also conducted. Finally, questionnaires about IAQ were administered to nursery teachers.

2.2. Air quality measurement

The monitoring approach included passive and direct-reading instrument methods. Passive sampling was done first in the non-heating period and then repeated in the heating period. Continuous air quality sensors measuring temperature, relative humidity (RH), particulate matter (PM_1, $PM_{2.5}$, PM_{10}) and total volatile organic compounds (TVOCs) were placed in the studied rooms from March 2021 to Feb 2022 (approximately 11 months) and at outdoor locations at the nursery grounds. A Summary of the main characteristics of each studied room is shown in Table 1. Air purifiers were used from May 2021 to Jan 2022. Details of the monitoring can be found in Table S1.

Direct-reading monitors (Eltek TU1082-AQ110/112) were installed and operated in three to five rooms and one outdoor site at each nursery. Twelve indoor and three outdoor locations were monitored in three nurseries in total. A summary of monitored parameters and resolution of the Eltek AQ110/112 sensors can be found in Table S2. Indoors, the monitors were installed at a height of 1.5–1.7 m above the floor to limit interruption of normal occupants' activities and to be out of the reach of children. Data was collected at 5 min intervals and uploaded to a cloud server via Eltek Squirrel SRV250 data loggers. All the sensors were co-located with reference instruments before and after the experiment.

Passive samplers were adjusted on plastic holders and attached on the wall at approximately 1.8 m height vertically with the open end downwards during sampling. The list of priority substances included VOCs commonly present in educational environments that have shown adverse health effects and hence are a potential hazard. Targeted VOCs were benzene, toluene, naphthalene, α-pinene, D-limonene, trichloroethylene (T3CE), tetrachloroethylene (T4CE), styrene, ethylbenzene, m-, p- and o-xylenes, 1,2,4-trimethylbenzene and 1,3,5-trimethylbenzene. Benzene, toluene, naphthalene, α-pinene, D-limonene, trichloroethylene (T3CE), tetrachloroethylene (T4CE) and styrene are the most common pollutants reported in nursery environments [7,28], and are mentioned in BB101 [29] (Building Bulletin 101: Guidelines on ventilation, thermal comfort and indoor air quality in schools) and by WHO [30] as potential hazards. In nurseries, children may breathe air contaminated with xylenes [31], which is why it was also included in targeted VOCs. In two studies on nurseries, 1,2,4-trimethylbenzene and 1,3,5-trimethylbenzene were detected at a relatively high concentration (exceeding 1 $\mu g/m^3$) [7,32]. Therefore, those two compounds were also included in this study. Aldehydes such as formaldehyde, acetaldehyde, propionaldehyde, butyraldehyde, benzaldehyde, valeraldehyde, and hexanaldehyde were analysed. Those aldehydes were the most commonly reported in studies about IAQ of nurseries [33,34]. Field blanks were used for each site and measurements period.

2.3. Window sensors

Window state (open/closed) was monitored in each nursery to assess the impact on indoor air quality and air purifier performance. The external doors and all the windows in each studied room were monitored by a window sensor (Eltek GS34) via magnetic reed switches.

2.4. Air purifier operation

In this study, the air purifier was set up to turned on during the whole occupancy period and the data of operation state was fully collected. The operation of the air purifiers was controlled by an internal timer. To check operation, an optical pulse meter was placed over an LED indicator on the purifier (flashing when the equipment was turned on). The children usually arrived around 9:00 a.m. and left around 3:00 p.m., the operation time of the air purifier was set up from 8:00 a.m. to 4:00 p.m. One nursery did not agree to put air purifiers in their classroom due to limited space and safety concerns, so air purifiers were installed in staffrooms. Six air purifiers were installed in three nurseries, with three air purifiers in staffrooms and three air purifiers in classrooms (See Table 1).

2.5. Questionnaire

The questionnaire was designed to gather information on four aspects: general characteristics of the nursery (occupant density, operation

Table 1
Summary of the main characteristics of each studied room.

Site	Room	Abbr.	Occupancy	Area (m^2)	Volume (m^3)	Air purifier	Ventilation
Nursery 1	classroom 1	N1_class1	33	35	105	No	Natural ventilation with openable windows and exterior doors
	classroom 2	N1_class2	33	41	160	No	
	classroom 3	N1_class3	20	48	190	No	
	staffroom 1[a]	N1_staff1	6	45	188	Yes (1 unit)	
	staffroom 2[b]	N1_staff2	4	48	193	Yes (1 unit)	
		N1_class5	20				
Nursery 2	classroom 1	N2_class1	22	55	210	No	
	classroom 2	N2_class2	12	36	85	No	
	staffroom 1[a]	N2_staff1	5	55	215	Yes (1 unit)	
	staffroom 2	N2_staff2	3	49	170	Yes (1 unit)	
Nursery 3	classroom 1	N3_class1	50–60	165	530	Yes (2 units)	
	classroom 2	N3_class2	20–30	55	180	No	
	classroom 3	N3_class3	25	71	140	No	

[a] Both rooms had been previously used as classrooms but were used as staffrooms during Covid-19 period.
[b] Staffroom 2 was used as a staffroom during non-heating season and a classroom (classroom 5) during heating season.

time); use of classroom space (window usage, product usage); use of air purifier (operation, noise level, performance feedback); and self-reported satisfaction with indoor environmental quality in the nursery. Survey structure and the content were based on those developed for SINPHONIE [35]. The printed questionnaire was administered to nursery teachers before the end of the experiment. There were 40 participants who answered the questionnaire. This research was approved by BSEER Ethics Team and was in line with UCL's Data Protection Policy.

3. Results

3.1. The impact of Covid-19 on ambient air quality

People's mobility was restricted during the Covid-19 period which led to reductions in vehicular traffic. Study [36] reported that the monthly-average daily traffic was reduced by 69% in April 2020 compared with April 2019, which resulted in mean reductions in NO_2 of 38.3% (8.8 μg/m^3) and $PM_{2.5}$ of 16.5% (2.2 μg/m^3) which may be reflected in lower pollutant levels indoors. In addition, occupant behaviour was affected by the Covid-19 response measures. For example, opening windows was recommended to help control the transmission of Covid-19, and frequent ventilation may also impact indoor environments.

3.2. Indoor air quality

3.2.1. Temperature, CO_2 and $PM_{2.5}$

The results of the continuous monitoring for temperature, CO_2 and $PM_{2.5}$ are shown in Fig. 1. In the non-heating season, the median indoor temperature levels (ranged between 18 °C and 26 °C) were typically within the comfort range (19 °C–25 °C) recommended by BB101 [29] and ASHRAE [37]. However, temperatures both above (nursery 2) and below (nursery 1) the comfort range were observed as shown in Table 2. In the classrooms of nursery 1, the percentage of time that temperatures were below the recommended level ranged from 30% to 47% (mean: 36%; during occupied period hours). In the classrooms of nursery 2, the mean percentage of time that temperatures were above the recommended level was 37% (during occupied period hours). When given the seven comfort level scales questionnaire, 56% participants gave a score <0 which indicates they were not satisfied with the thermal condition during the heating season.

As may be expected under the higher ventilation recommendations for control of Covid-19 infection, the median indoor CO_2 levels in this study were relatively low and ranged between 364 and 702 ppm. The median indoor $PM_{2.5}$ levels in this study ranged between 0.3 and 6.1 μg/m^3 (rooms with purifiers had median concentrations between 0.3 and 2.5 μg/m^3, and rooms without air purifiers had median concentrations between 3.3 and 6.1 μg/m^3). In most studied rooms, median concentrations were under the 5 μg/m^3 (annual average exposure) recommended by WHO [43]. However, in 7 of the classrooms without air purifier, only 54% of total occupied hours were below 5 μg/m^3 across the study as shown in Table 3. For rooms with air purifiers, the total occupied hours below 5 μg/m^3 was as much as 88%. As previously noted, outdoor concentrations averaged 5.3 μg/m^3 in the heating season and 11.3 μg/m^3 in the non-heating season, corresponding with lower concentrations during the Covid-19 pandemic.

3.2.2. NO_2 and O_3

As shown in Table 4, indoor NO_2 levels were higher than the new guideline value of 10 μg/m^3 (annual mean) recommended by WHO [43]. All classrooms exceeded this new guideline, with concentrations ranging between 11.2 and 24.6 μg/m^3. NO_2 is a traffic related pollutant and mainly from outdoors, which is reflected here in Indoor/Outdoor (I/O) ratios mostly less than 1. Outdoor and indoor NO_2 levels were higher in the heating season, but I/O ratios from passive sampling between heating and non-heating seasons were similar, with averages of 0.83 and 0.79 respectively. The indoor O_3 levels were considerably lower than those outdoors. As O_3 could be reactive with indoor surface material, and no indoor sources (like printer) were reported, the low I/O ratios suggest that the primary source of O_3 was from outdoor environments.

3.2.3. VOCs

All studied VOC concentrations are shown in Table 6. The TVOC levels were under 300 μg/m^3 suggested by The Building Regulations 2010 Approved Documents: part F [46] in all studied rooms. Similarly, most specified VOCs were measured at concentrations lower than guideline values (Table 6), except for 2-ethylhexanol (ranging from 0.4 to 20.4 μg/m^3). For most VOCs, the indoor levels were relatively low compared to previous studies focusing on nurseries in other countries. Table 5 shows the measured concentrations of BTEX (benzene, toluene, ethylbenzene and m/p/o-xylenes) and naphthalene concentrations in comparison to other nursery studies [28,33,34,38,47].

3.2.4. Aldehydes

As shown in Table 7, formaldehyde, acetaldehyde, butyraldehyde and hexanaldehyde were detected in this study. Propionaldehyde, benzaldehyde and valeraldehyde were below the limit of detection and are not included in Table 7. Notably, formaldehyde levels were higher than other pollutants, with a mean of 29.0 μg/m^3 in the non-heating season and 18.9 μg/m^3 in the heating season. Moreover, all the studied rooms had formaldehyde levels exceeding 10 μg/m^3, the limit recommended by Public Health England [48].

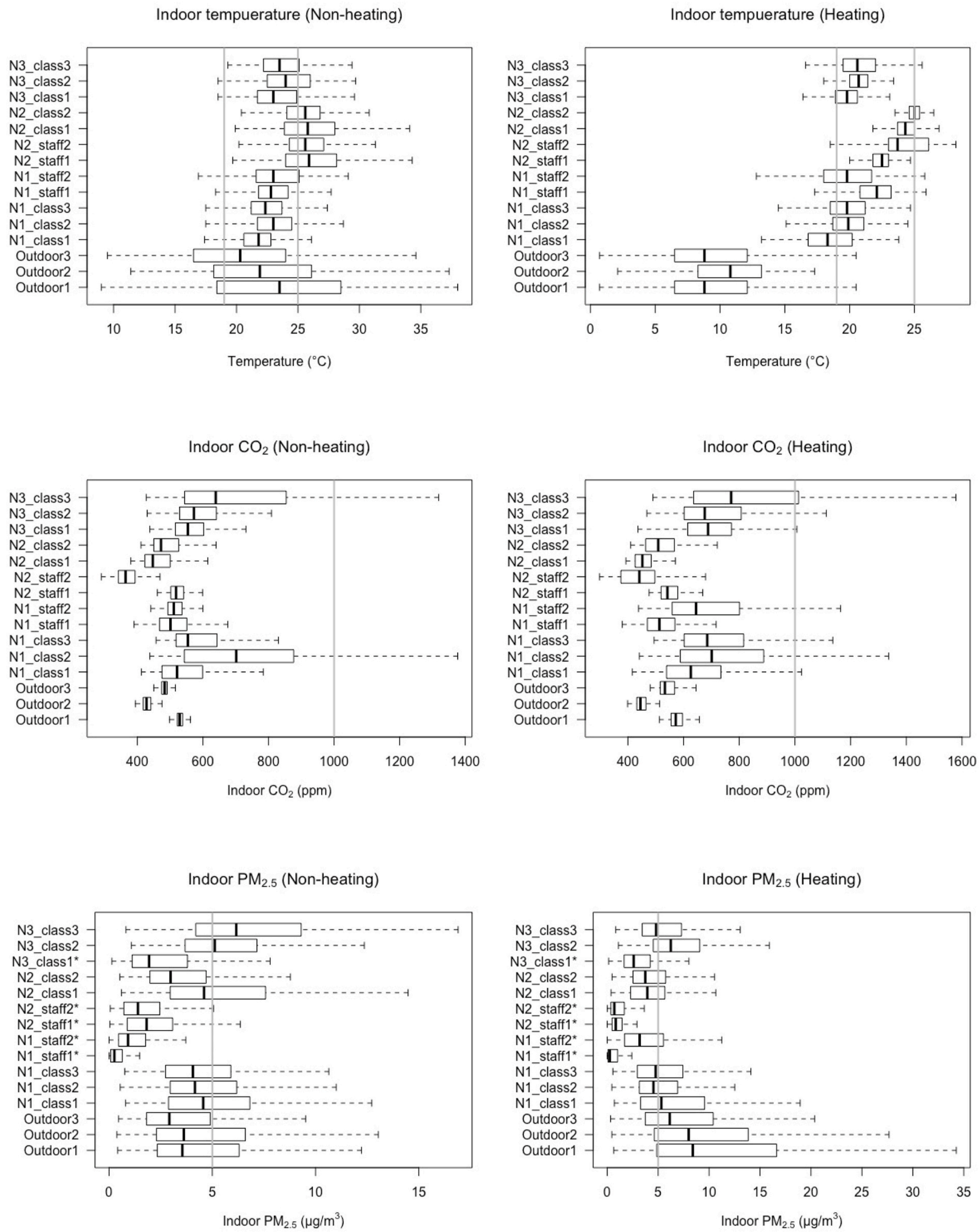

Fig. 1. Descriptive statistics of outdoor and indoor environmental variables (monitoring period: March 2021 to Feb 2022); *rooms with air purifiers.

3.3. Window operation behaviour

As shown in Table 8, the percentage of time windows or doors were open was higher in the non-heating period than in the heating period in most studied rooms. In classrooms, at least one window was opened for 77%–92% of occupied hours (mean 85%) in the non-heating season and 20%–90% in the heating season (mean 58%). Some classrooms saw behaviour changes between the heating and non-heating seasons as shown in Fig. 2, which may have been caused by Covid related policies, or the preference of the nursery teacher mainly using the room.

The results from the questionnaires showed that ventilation was the dominating driver of window operation. Getting fresh air (32%), concerns about Covid-19 (28%), cooling the space (24%) and allowing children outside (16%) were selected as the main reasons for window

Table 2
Percentage of total occupied hours **not** in thermal comfort range.

Temperature	Room	Above recommended level	Below recommended level	All
Nursery 1	Classroom 1	2%	47%	49%
	Classroom 2	5%	30%	35%
	Classroom 3	4%	32%	36%
	Staffroom 1	7%	12%	19%
	Staffroom 2	9%	24%	33%
Nursery 2	Classroom 1	38%	4%	43%
	Classroom 2	35%	11%	45%
	Staffroom 1	33%	6%	39%
	Staffroom 2	31%	4%	35%
Nursery 3	Classroom 1	9%	11%	21%
	Classroom 2	15%	4%	19%
	Classroom 3	11%	5%	16%

Table 3
Percentage of total occupied hours in recommended ranges ([a]rooms with air purifiers).

	Room	Temperature	CO_2	$PM_{2.5}$
Nursery 1	Classroom 1	51%	97%	51%
	Classroom 2	66%	87%	58%
	Classroom 3	64%	93%	57%
	Staffroom 1[a]	81%	100%	100%
	Staffroom 2[a]	68%	95%	80%
Nursery 2	Classroom 1	58%	100%	64%
	Classroom 2	55%	100%	71%
	Staffroom 1[a]	61%	100%	88%
	Staffroom 2[a]	65%	100%	97%
Nursery 3	Classroom 1[a]	80%	99%	74%
	Classroom 2	81%	96%	41%
	Classroom 3	84%	77%	37%
	Mean	68%	95%	54%[a]
	Mean (rooms with air purifier)			88%

[a] Rooms with air purifier were excluded.

and external door operation. Furthermore, when asked in the questionnaire, "During Covid-19, do you open the windows more often than usual?", all participants agreed that they opened windows more often than before Covid-19, even in the heating season, indicating that temperature was a less important factor in window and door operations. As a result, 56% of participants reported thermal discomfort during the heating season (giving a score <0, on a seven comfort level scale).

3.4. Air purifier and its operation

Based on the results of questionnaire received from 40 nursery staff (22 participants were in the room with air purifier), 91% of the 22 participants did not perceive any difference in air quality between the rooms with and without air purifiers operating. When asked "the reasons for manually turning off the air purifier", 68% of participants answered "No" and 27% participants addressed that they turned off the air purifier as "the air purifier is noisy". Some participants reported that sometimes they felt distracted by the noise generated by the air purifier, and therefore turned it off.

Noise and performance of air purifiers were scored by the occupant based on seven likert scale questions. Fig. 3 shows the evaluation of noise and performance of air purifiers, 55% (12/22) of occupants considered them quiet (giving a score <0), while 36% (8/22) of occupants considered them noisy (giving a score >0). As for the performance of air purifiers, 45% (10/22) of occupants gave positive feedback about the overall performance of the air purifier (giving a score >0), while 27% (6/22) of occupants gave negative feedback (giving a score <0). Notably, participants who considered the air purifier to be noisy also gave a low score for the performance of the air purifiers. The correlation between scores of the noise and the performance of air purifiers is also strong ($r: -0.93, P < 0.01$).

3.5. Impact of air purifiers on IAQ

Fig. 4 illustrates the differences of $PM_{2.5}$ concentrations in studied rooms when air purifiers were either off or on (occupied hours only). Physical characteristics of rooms with air purifiers were shown in Table 9. Even in staffrooms, which tended to have lower PM levels than classrooms, the reductions are clear. It is worth noting that when the air purifiers were turned off, the mean $PM_{2.5}$ concentrations in two classrooms were 6.6 μg/m^3 and 7.3 μg/m^3, which were higher than the WHO guideline of 5 μg/m^3 (annual mean). However, the air purifiers lowered the $PM_{2.5}$ concentrations below the recommended level (3.4 μg/m^3 and 2.3 μg/m^3) in those classrooms.

3.6. Impact of air purifier and window operation on IAQ

Fig. 5 shows the indoor $PM_{2.5}$ decay curves during the period of air purifier operation when opening and closing windows. Note, as purifiers typically started 1 h before opening hours, peaks, likely associated with resuspension following the children's arrival (around 9:00 a.m.), can often be seen around 60 min after the purifier started operating. The plot aggregated the data during whole operation period of air purifier (around 200 days), which includes different outdoor conditions and indoor activities.

The air purifiers most effectively reduced indoor $PM_{2.5}$ when windows were closed (red lines), which was also reported by other studies [49,50]. As shown in Table 10, for rooms without intense activity (staffrooms), the reduction rate reached 68% with the window closed, compared with 31% when window was open. For all rooms, the mean reduction rate was 63% with window closed, and 46% with window open. The mean of reduced $PM_{2.5}$ level was 2.4 μg/m^3 and 1.4 μg/m^3 with window open and window closed, respectively. However, air purifiers can still reduce the mean concentration of indoor $PM_{2.5}$ from the initial concentration of 4.5 to 2.4 μg/m^3 when windows were open.

4. Discussion

4.1. IAQ and window operation

Covid-19 response measures could impact the behaviour, including changes in energy-related behaviours, decision-making and daily routines [51]. Previous studies reported that the operation of windows was mainly related to temperature, and people tend to open widows more frequently in higher temperatures [14–16,52]. In this study, the questionnaire showed that occupants have concerns about Covid-19, so they opened the windows more often than usual to get fresh air, which may bring thermal discomfort. Similarly, a study in Sevilla also mentioned that, during the pandemic, over 60% of hours were outside of thermal comfort conditions in primary school classrooms [10]. The results from the questionnaire in this study that 56% participants were not satisfied with the thermal condition during the heating season also support this previous finding by Alonso et al. (2021). In this circumstance, the need for increased ventilation (window operation) and maintaining a comfortable temperature should be balanced [11]. One limitation of this

Table 4
Results of NO_2 and O_3 concentrations of outdoors and indoor (all filed blanks were recorded under their respective limits of detection LoD).

Location		NO_2 (μg/m^3)[a]		I/O ratio of NO_2		O_3 (μg/m^3)[b]		I/O ratio of O_3[c]	
		Non-heating	Heating	Non-heating	Heating	Non-heating	Heating	Non-heating	Heating
Nursery 1	Outdoor 1	–	31.55	–	–	–	26.52	–	–
	Outdoor 2	20.74	29.63	–	–	53.09	22.11	–	–
	Classroom 1	17.38	19.61	0.84	0.66	8.49	<7.86	0.16	0.16
	Classroom 2	16.43	21.25	0.79	0.72	<5.70	<7.86	0.05	0.16
	Classroom 3	15.13	21.78	0.73	0.74	<5.71	<7.86	0.05	0.16
	Staffroom 1	16.11	19.08	0.78	0.64	<5.71	<7.86	0.05	0.16
	Staffroom 2	17.07	21.94	0.82	0.74	5.79	<7.86	0.11	0.16
Nursery 2	Outdoor 1	–	28.69	–	–	–	36.27	–	–
	Outdoor 2	20.64	26.05	–	–	40.21	22.52	–	–
	Classroom 1	16.85	24.56	0.82	0.94	<5.09	<8.03	0.06	0.14
	Classroom 2	16.12	21.36	0.78	0.82	<5.09	<8.03	0.06	0.14
	Staffroom 1	18.59	31.63	0.90	1.21	6.32	<8.03	0.16	0.14
	Staffroom 2	18.27	22.30	0.89	0.86	7.09	<8.03	0.18	0.14
	Classroom 3	–	23.12	–	0.89	–	<8.03	–	0.14
	Classroom 4	–	22.39	–	0.86	–	<8.03	–	0.14
Nursery 3	Outdoor 1	38.82	40.13	–	–	–	22.37	–	–
	Outdoor 2	21.04	29.57	–	–	29.28	18.13	–	–
	Classroom 1	15.03	23.26	0.71	0.79	<8.38	<6.95	0.14	0.17
	Classroom 2	19.60	23.49	0.93	0.79	<8.38	<6.95	0.14	0.17
	Classroom 3	20.10	11.15	0.96	0.38	8.93	<6.95	0.31	0.17

[a] Non-heating: overall measuring uncertainty: ±9.7%, limit of detection: 0.030 μg NO_2; heating: overall measuring uncertainty: ±9.7%, limit of detection: 0.028 μg NO_2.
[b] Non-heating: overall measuring uncertainty: ±10.2%, limit of detection: 0.49 μg/ml O_3^-; heating: overall measuring uncertainty: ±10.2%, limit of detection: 0.13 μg/ml O_3^-.
[c] When calculating I/O ratios for O_3, values that are below the limit of detection (LoD) or limit of quantification (LoQ) are substituted with LoD/2 or LoQ/2, respectively [45].

Table 5
Mean VOCs compared with other nursery studies.

Mean (μg/m^3)	PHE[a] guidelines	This study	Canha et al., 2016	Mainka et al. 2015[b]	St-Jean et al., 2012	Roda et al., 2011
benzene	No safe level	0.4	2.1	3.2	1.8	2.0
toluene	2300 (1 day)	1.9	5.2	8.7	7.5	7.3
ethylbenzene	–	0.3	2.2	3.6	1.5	1.3
m/p-xylenes	100 (1 year)	1.5	4.4	–	5	3.9
o-xylene	100 (1 year)		1.6	–	1.4	1.4
Naphthalene	3.0 (1 year)	0.2	–	1.0	0.9	–

[a] Public Health England [48].
[b] Mean level of four studied rooms.

research is that data about the window usage before Covid-19 in nursery environments is limited, and it is, therefore, hard to directly compare the window behaviour before and after Covid-19. Future studies should investigate window status and its relationship with IAQ and thermal comfort, in order to evaluate the further changes of occupant behaviour in the post-Covid period [9].

Frequent ventilation during Covid-19 is a possible reason that pollutant levels indoors were found to be relatively low. A recent study highlighted the improved IAQ during Covid-19 in primary schools (naturally ventilated classrooms), with reductions of 400 ppm in CO_2 during the pandemic [10]. Mean indoor CO_2 concentrations in this study were also lower than previous studies that focused on IAQ in nurseries (range: 447–2570 ppm) [33,38,39]. However, some CO_2 peaks higher than 1000 ppm were observed at nursery 1 and nursery 3, which may be indicative of some periods overcrowding and inadequate ventilation. Studies in other countries reported that the mean indoor $PM_{2.5}$ levels ranged from 19.7 to 69.5 μg/m^3 [34,40–42]. In our study, the median indoor $PM_{2.5}$ levels (rooms without air purifier) ranged between 3.3 and 6.1 μg/m^3. However, high indoor NO_2 levels that exceeded the WHO guideline level were observed. The health impact of NO_2 is primarily on the respiratory system. NO_2 was identified as a significant contributor to a high number of childhood asthma cases in Chinese urban areas [53]. A study before Covid-19 reported that the I/O ratios of NO_2 in schools were 0.59 in heating season [44], which was lower than the ratios observed in this study (0.83). The changes of I/O ratios again indicate increased ventilation during the Covid-19 pandemic, which has led to the introduction of outdoor pollutants. At present, effective filtration of NO_2 remains challenging, particularly in naturally ventilated buildings. As sufficient ventilation rates are required for diluting internal pollutants and to reduce the risk of virus transmission, reducing ambient concentrations may be key to reducing exposure indoors. Mitigation strategies such as the promotion of new energy vehicles and the transition from gas stoves to electric stoves have been suggested to mitigate outdoor and indoor emissions [53].

The detected formaldehyde (ranged from 9.5 to 65.0 μg/m^3) and 2-ethylhexanol (ranged from 0.43 to 20.4 μg/m^3) were high and should be noted. As other pollutants were diluted by frequent window opening (higher ventilation), high levels of formaldehyde and 2-ethylhexanol could indicate that those pollutants are even higher when not under Covid-19 conditions. Vinyl floors (present in all three nurseries) have been identified as a major source of 2-ethylhexanol [54]. A review paper mentioned that exposure to even low levels of 2-ethylhexanol over time may cause health effects such as SBS symptoms, mucosal irritation and influence central nervous system [54]. In Finland, a study reported 2-ethylhexanol levels ranging from 1 to 4 μg/m^3 in a school building with complaints from the children of symptoms such as irritation in the respiratory tract and eyes [55]. The presence and concentration of this pollutant, and its reported health effects, warrants further examination to establish guidelines for indoor air. The highest formaldehyde level captured in this study was 65 μg/m^3, which was in a classroom with only one external door and a small window for ventilation as well as plywood furniture. High indoor formaldehyde levels in nursery environments were also reported in other studies with maximum levels of 28.5 μg/m^3 [56] and 50 μg/m^3 [57]. Common indoor sources include building materials and wooden/plywood furniture. Long-time exposure to

Table 6
Outdoor and indoor VOCs levels; class refers to classroom and staff refers to staffroom; m-, p-xylenes and o-xylenes were co-eluted (eluted together in a chromatography process) during analysis.

VOCs	Season		Nursery 1						Nursery 2							Nursery 3			
($\mu g/m^3$)		ELV	Outdoor	Indoor					Outdoor	Indoor						Outdoor	Indoor		
		Source		C1	C2	C3	S1	S2		C1	C2	S1	S2	C3	C4		C1	C2	C3
TVOC	Non-heating	300	63.1	166.8	230.1	268.0	255.3	203.2	46.4	78.9	174.5	78.5	63.2	–	–	29.7	247.4	162.3	89.5
	Heating	(BB 101)	42.6	85.5	93.3	79.1	137.8	78.0	39.1	–	123.6	–	132.8	74.8	75.7	150.3	205.1	194.7	279.2
Benzene	Non-heating	No Safe Level	0.14	0.09	0.08	0.08	0.14	0.15	0.35	0.20	0.18	0.19	0.23	–	–	0.12	0.22	0.10	0.10
	Heating	(PHE)	0.71	0.68	0.66	0.57	0.64	0.57	0.72	–	0.60	–	0.53	0.58	0.67	1.47	1.13	1.14	1.03
Toluene	Non-heating	2300	0.43	1.26	1.09	1.52	1.81	0.91	1.13	1.29	1.83	1.64	1.48	–	–	1.87	3.09	2.06	1.96
	Heating	(PHE)	0.93	1.51	1.57	1.61	2.00	1.45	0.95	–	1.64	–	1.08	1.01	2.06	4.22	3.25	3.56	4.17
Ethylbenzene	Non-heating	–	<0.04	0.14	0.15	0.22	0.28	<0.04	<0.04	0.06	0.06	0.13	<0.04	–	–	<0.04	0.29	0.12	0.07
	Heating	–	0.22	0.30	0.29	0.25	0.31	0.23	0.14	–	0.25	–	0.19	0.19	0.26	0.71	0.68	0.73	0.66
o/m/p-Xylene	Non-heating	100	0.19	0.96	0.93	1.17	1.55	0.24	0.63	0.83	0.82	1.25	0.83	–	–	0.87	1.87	1.17	1.00
	Heating	(PHE)	1.00	1.49	1.44	1.11	1.44	1.19	0.83	–	1.35	–	0.95	0.90	1.29	3.63	3.62	4.31	3.36
Styrene	Non-heating	850	<0.04	<0.04	<0.04	<0.04	0.24	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	–	–	<0.04	<0.04	<0.04	<0.04
	Heating	(PHE)	<0.04	0.16	0.15	0.15	0.32	0.14	<0.04	–	0.28	–	0.14	0.13	0.26	0.36	0.36	0.34	0.46
135TMB	Non-heating	–	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	–	–	<0.03	<0.03	<0.03	<0.03
	Heating	–	<0.03	0.03	0.03	<0.03	<0.03	<0.03	<0.03	–	0.04	–	<0.03	<0.03	<0.03	0.07	0.07	0.07	0.08
124TMB	Non-heating	–	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	–	–	<0.03	<0.03	<0.03	<0.03
	Heating	–	0.08	0.16	0.15	0.11	0.11	0.10	0.05	–	0.13	–	0.08	0.07	0.11	0.27	0.32	0.35	0.34
Naphthalene	Non-heating	3.0	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	–	–	<0.03	<0.03	<0.03	<0.03
	Heating	(PHE)	<0.03	0.11	0.11	0.13	0.12	0.10	<0.03	–	0.06	–	0.03	0.04	0.03	0.06	0.08	0.09	0.09
α-Pinene	Non-heating	4500	<0.05	0.38	0.26	0.65	1.75	0.59	<0.05	0.20	2.17	0.25	<0.05	–	–	<0.05	2.06	0.11	0.08
	Heating	(PHE)	<0.05	0.60	0.53	0.35	1.36	0.47	<0.05	–	1.37	–	0.92	0.99	1.33	0.48	1.39	1.27	3.62
Limonene	Non-heating	9000	<0.05	1.91	2.22	6.46	1.69	2.13	<0.05	<0.05	0.53	0.99	0.99	–	–	<0.05	21.3	14.6	1.34
	Heating	(PHE)	<0.05	6.48	6.27	2.32	9.58	1.63	<0.05	–	11.8	–	3.05	3.84	28.9	12.7	8.50	18.1	19.4
Ethylhexanol	Non-heating	–	<0.04	1.08	0.83	4.73	3.19	3.10	<0.04	1.95	4.81	2.00	0.43	–	–	<0.04	4.41	20.4	9.42
	Heating	–	0.08	0.95	0.90	1.38	1.84	1.26	0.04	–	2.60	–	1.13	1.37	1.90	0.53	11.3	12.7	8.07
Trichloroethylene	Non-heating	No Safe Level	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	–	–	<0.05	<0.05	<0.05	<0.05
	Heating	(PHE)	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	–	<0.05	–	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Tetrachloroethylene	Non-heating	40	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	–	–	<0.05	<0.05	<0.05	<0.05
	Heating	(PHE)	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	–	<0.05	–	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
1,4-Dichlorobenzene	Non-heating	–	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	–	–	<0.05	<0.05	<0.05	<0.05
	Heating	–	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	–	<0.05	–	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05

Note: The LoD was 0.001 ppb by application of sampling rates and sample exposure period. The LoQ was 0.01 ppb. The method used is based on the international standard: ISO 16017-2:2003; the overall uncertainty is 30%.

Table 7
Outdoor and indoor aldehyde levels; not detected (ND) represents results below the LoD and not quantified (NQ) represents results below the LoQ; C is classroom and S is staffroom.

Aldehydes ($\mu g/m^3$)	Season	Nursery 1 Outdoor	Nursery 1 Indoor C1	C2	C3	S1	S2	Nursery 2 Outdoor	Nursery 2 Indoor C2	C3	S1	S2	C4	C5	Nursery 3 Outdoor	Nursery 3 Indoor C1	C2	C3
Formaldehyde[a]	Non-heating	2.8	21	25	20	48	24	4.0	29	65	31	36	–	–	2.5	21	18	9.5
	Heating	1.9	–	ND	13.5	36.9	11.9	2.5	–	31.1	–	22.7	13.6	12.1	2.4	10.5	12.8	24.3
Acetaldehyde[b]	Non-heating	ND	2.4	1.7	2.4	3.9	2.5	ND	2.0	3.4	3.3	3.0	–	–	0.87	4.4	1.9	1.1
	Heating	ND	–	3.1	3.5	4.6	3.0	NQ	–	3.7	–	3.1	3.5	2.8	NQ	3.0	3.4	4.7
Butyraldehyde[c]	Non-heating	ND	0.73	ND	0.64	1.4	1.3	ND	2.0	3.4	3.3	3.0	–	–	ND	0.77	ND	ND
	Heating	ND	–	ND	ND	ND	ND	ND	–	ND	–	ND	ND	ND	ND	ND	ND	ND
Hexaldehyde[d]	Non-heating	1.6	9.6	8.4	8.9	12	6	1.8	7.8	16	8.2	6.2	–	–	ND	11	5.1	3.6
	Heating	1.6	–	3.9	4.2	11.2	3.4	2.0	–	9.8	–	6.2	5.1	5.0	1.8	3.0	3.8	7.9

Note: the method used is based on the international standard: ISO 16000-4:2011; accuracy is stated on the operating instructions of the sampler as ±25%.
[a] Non-heating: LoD: 0.29 $\mu g/m^3$; LoQ: 0.96 $\mu g/m^3$; heating: LoD: 0.4 $\mu g/m^3$; LoQ: 1.3 $\mu g/m^3$.
[b] Non-heating: LoD: 0.13 $\mu g/m^3$; LoQ: 0.44 $\mu g/m^3$; heating: LoD: 0.7 $\mu g/m^3$; LoQ: 2.5 $\mu g/m^3$.
[c] Non-heating: LoD: 0.19 $\mu g/m^3$; LoQ: 0.64 $\mu g/m^3$; heating: LoD: 0.2 $\mu g/m^3$; LoQ: 0.6 $\mu g/m^3$.
[d] Non-heating: LoD: 0.17 $\mu g/m^3$; LoQ: 0.58 $\mu g/m^3$; heating: LoD: 0.3 $\mu g/m^3$; LoQ: 1.0 $\mu g/m^3$.

formaldehyde may related to various symptoms including neurasthenia, irritation, inflammatory, abdominal pain, etc [58]. A review paper claimed that the odds ratios for children asthma were 1.27 (eastern country) and 1.03 (western country) per 10 $\mu g/m^3$ increase in formaldehyde concentration, respectively [59]. As ventilation behaviour may change in post-Covid period, indoor formaldehyde could rise to a higher level and should be monitored and studied in future studies.

4.2. Operation and performance of air purifier

Although the median $PM_{2.5}$ levels in most studied classrooms were lower than the guideline of 5 $\mu g/m^3$ (the annual average exposure) suggested by WHO [43], in the classrooms without air purifier, only 54% of total occupied hours fulfilled the WHO guideline (in rooms with air purifier, the percentage could reach 89%). As the correlation between occupants' perceived air quality and indoor pollutants (like PM) is low [60], the driver of air purifier operation may not be directly related to air quality. Studies directly focusing on air purifier use and its drivers were limited. In a pervious study in homes [22], occupants perceived that the air purifier provided a cooling effect in a room, and there was a clear correlation between increasing temperatures and the use of air purifiers. However, participants in this research didn't report the "cooling effect" of air purifiers, as the outlet of the air purifier model was on the top of the device at a height of around 190 cm. In this study, noise level was the critical factor impacting the operation of air purifiers. A study reported a mean sound level in nursery classrooms of 70.87 ± 2.5 dB(A), which illustrates that nursery are normally high sound level environments [61]. In this study, most occupants who reported that the air purifier was noisy were from staffrooms which have lower background noise levels compared to classrooms. The noise level of the air purifiers was around 56 dB(A) which would not contribute substantially to the already high background noise levels of nursery classrooms reported by Eysel-Gosepath et al. (2010). However, for primary and secondary schools or residential buildings where noise could easily affect occupants [65], the noise level should be taken into consideration in the assessment of the factors affecting air purifier operation. Additionally, occupants might interpret quiet air purifiers as less effective. A study [62] reported a positive association between noise level and CADR (clean air delivery rate), that is devices with higher CADRs usually had higher noise levels. The operation state of air purifiers is important to accurately evaluate performance but is often not documented in previous studies. Inadequate operation hours could be a possible reason to explain the low efficiency from previous studies [20]. Another limitation of this study is that due to limited access to the nursery during Covid-19 and consideration of efficiency of air purifier, the air purifiers were set to operate at the same speed and operation hours. As a result, data are not available for air purifier use at different speeds (and noise levels) to test the relationship between noise and the use of air purifiers. Future work should more specifically explore the impact of noise levels on operational behaviour to improve the real-world performance and encourage air purifier usage [26].

The performance of the air purifier might be affected by the operation of windows and the level of outdoor air pollution. For instance (Fig. 5), in nursery 2, staff2 is directly adjacent to a road and peaks in $PM_{2.5}$ occurred primarily when the windows were open. Similarly, in nursery 1, class5 was next to a parking site of a police station. This parking site likely contributes to indoor air pollution when windows are open. When evaluating the performance of the air purifier, season and region factors should be considered, as there may be variations in window operation and outdoor pollution levels [63]. Future studies may focus on investigating the impact of these factors to provide a more comprehensive understanding of the purifier's performance under different conditions [66]. During the Covid-19 pandemic, occupants were encouraged to open windows more frequently and for longer periods of time. Additionally, air purifiers were recommended for use in some indoor spaces [64]. These two suggestions for the improvement of

Table 8
Window operation data in different seasons during occupied hours; 'd' indicates a door and 'w' indicates a window.

Site	Room	Percentage of time at least one window was opened in each room		Site	Room	Percentage of time at least one window was opened in each room	
		Non-heating	Heating			Non-heating	Heating
				Nursery 2	Staffroom 1	62%	21%
Nursery 1	Classroom 1	77%	84%		Staffroom 2	63%	17%
	Classroom 2	80%	33%		Classroom 1	87%	–
	Classroom 3	79%	50%		Classroom 2	–	41%
	Staffroom 1	36%	25%	Nursery 3	Classroom 1	90%	84%
	Staffroom 2	60%	57%		Classroom 2	90%	90%
					Classroom 3	92%	20%

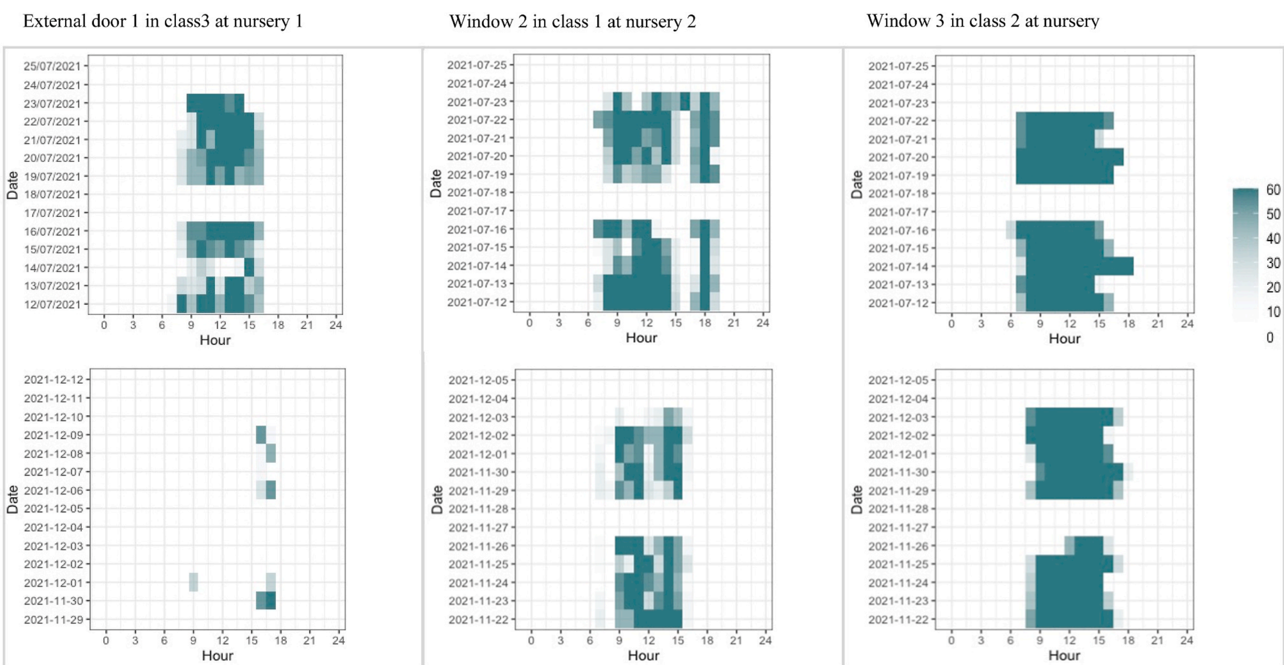

Fig. 2. Window open status per hour (percentage of time in the open state). Top: two weeks non-heating season. Bottom: two weeks heating season.

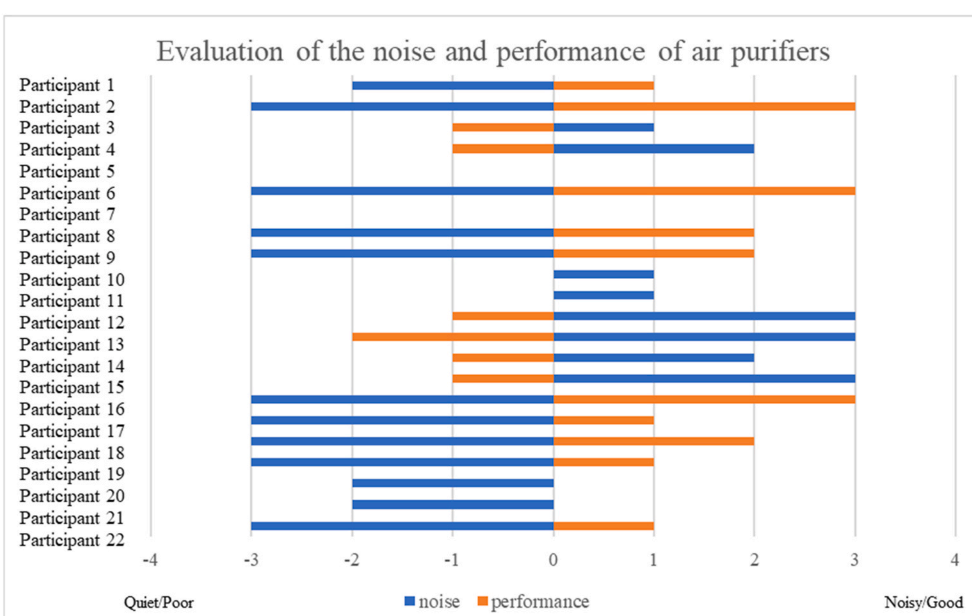

Fig. 3. Scores of the noise and performance of air purifiers evaluated by occupants. Bule boxes are the noise score, red boxes are the performance score.

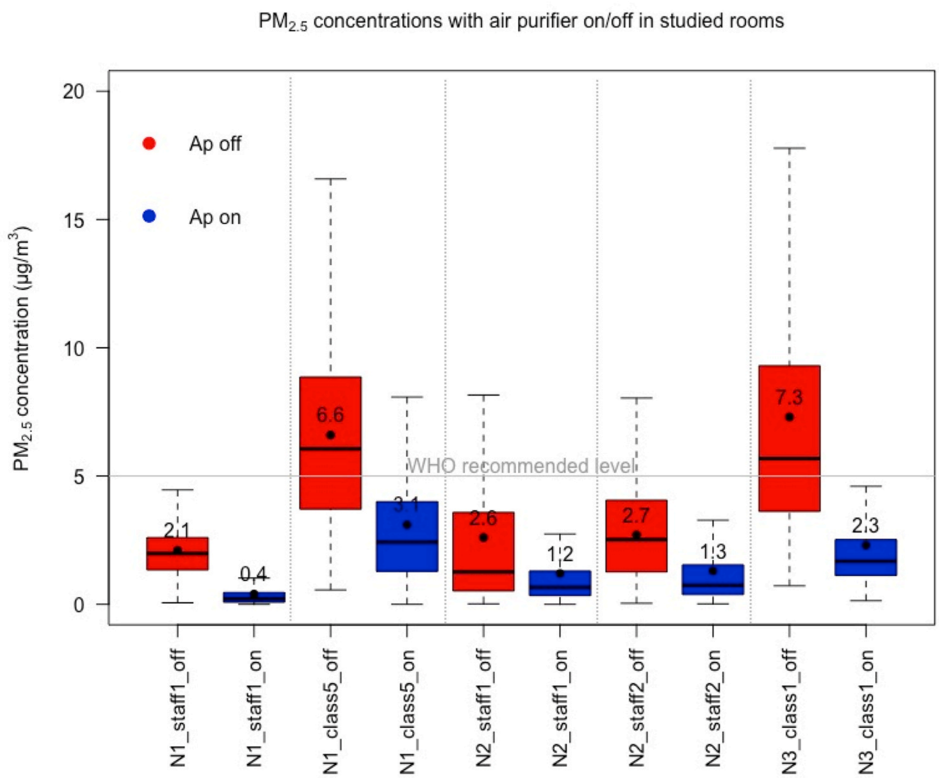

Fig. 4. p.m.$_{2.5}$ concentrations in rooms with air purifiers; red boxes are when air purifiers were turned off; blues boxes are when air purifiers were turned on; the air flow rate of the air purifier selected is 820 m^3/h, and the ideal ACH (air change per hour) for air purifier was kept around 3–4 in all studied rooms.

Table 9
Physical characteristics of monitored rooms.

Room	Room Volume (m^3)	Glazed area (m^2)	Effective opening area (m^2)	Number of air purifier	Air flow rate of air purifier (m^3/h)	ACH[a]
N1_staff1	188	28.2	12.8	1	820	4.4
N1_class5	193	25.6	10.6	1		4.3
N2_staff1	215	7.3	3.2	1		3.8
N2_staff2	170	11.4	5.8	1		4.8
N3_class1	530	6.2	6.2	2		3.1

[a] ACH of using air purifier without other ventilation methods.

indoor air to reduce airborne transmission of SARs-CoV-2 have the potential to conflict with the mitigation of other indoor air contaminants, as air purifier tend to achieve better performance with windows closed. In this study, even with windows opened, air purifier can still reduce the indoor $PM_{2.5}$ from initial concentration of 4.5 to 2.4 μg/m^3. Overall performance could be further improved if windows are only operated in situations when the outdoor air is likely to be as good as, or better than, indoor air. Therefore, locations near outdoor pollutant sources should be a consideration when providing operational guidance to occupants. Communication of operational guidelines and risks should be included with air purifiers to optimise their performance to reduce exposure to airborne contaminants from both indoor and outdoor sources.

5. Conclusions

This study measured indoor air quality in three London nurseries, across 9–11 months and included monitoring of window opening and air purifier use. The study took place in the context of Covid-19 with the associated recommendations for increased natural ventilation. This was observed through window measurements, with at least one window being open in classroom for 85% on the non-heating season and 58% of the heating season. These window operation behaviours could increase ventilation but increases the likelihood of thermal discomfort in the heating season. In this study, the highest percentage of time that classroom temperatures were below recommended levels was 47%. When increased ventilation (window operation) is needed, thermal comfortable should also be carefully considered.

In terms of air quality, CO_2, $PM_{2.5}$ and TOVCs concentrations were both low compared to previous studies in both seasons. Nitrogen dioxide concentrations were above the new WHO guidelines in all classrooms (mean indoor level 17.2 μg/m^3). Of the 12 measured VOCs and 7 measured aldehydes, formaldehyde (range from 9.5 to 65.0 μg/m^3) was above guideline values, with concentrations of other measured pollutants lower than previous nursery studies. Also, 2-ethylhexanol (range from 0.43 to 20.4 μg/m^3) was higher than the results reported by one other study [55]. Those two pollutants should be noted, as they all related to negative health effects and may rise to higher levels in the future.

For $PM_{2.5}$, the median level in most studied classrooms was lower than the guideline of 5 μg/m^3 (the annual average exposure) suggested by WHO [43], but high peaks were frequently observed. In the classrooms without an air purifier, only 54% of the total occupied hours had $PM_{2.5}$ levels below 5 μg/m^3. Air purifiers were effective at reducing mean $PM_{2.5}$ levels by 46% (with window open) and 63% (with window closed), increasing the total occupied hours with $PM_{2.5}$ below 5 μg/m^3 to 88%. This level of IAQ improvement could substantially reduce exposure of $PM_{2.5}$ to children in nursery care. Furthermore, when evaluating the performance of air purifiers, the window state (ventilation), outdoor pollution level as well as the seasonal and regional background should be taken onto consideration.

In terms of air purifier operation, noise levels were observed to be a key factor in the use of the devices. Noise levels and CADR are positively related, therefore both of these factors should be considered in air purifier selection and operation (including user instruction). Future work is

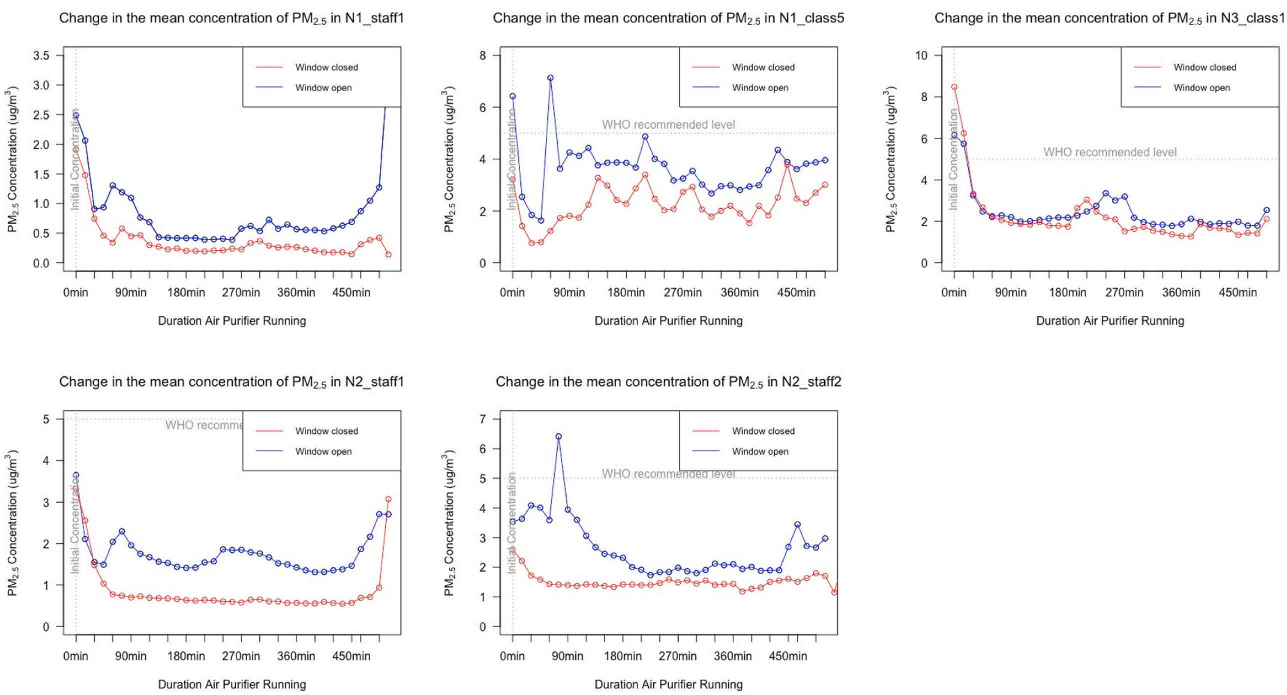

Fig. 5. Change in the mean concentration of $PM_{2.5}$ in rooms with air purifiers. Air purifiers were turned ON at 0min, they were programmed to start to operate at 8:00 a.m. and stop at 4:00 p.m. Note: As purifiers were set up to run approximately 60 min before fully occupied, a secondary peak is often seen around this time, as students enter the classroom in the morning at the same time.

Table 10
Initial and reduced $PM_{2.5}$ concentrations in rooms with air purifier (operated with open/closed window).

$PM_{2.5}$ (μg/m^3)	Window open			Window closed		
	Initial level	Reduced level	Reduction	Initial level	Reduced level	Reduction
N1_staff1	2.5	1.3	48%	1.9	0.4	79%
N1_class5	6.4	3.8	41%	3.2	2.7	16%
N2_staff1	3.7	2.7	27%	3.3	0.9	73%
N2_staff2	3.5	2.7	23%	2.5	1.2	52%
N3_class1	6.2	1.6	74%	8.2	1.8	78%
Mean (class)	6.3	2.7	57%	5.7	2.3	61%
Mean (staff)	3.2	2.2	31%	2.6	0.8	68%
Mean (all)	4.5	2.4	46%	3.8	1.4	63%

needed to understand what this reduction in exposure means for any potential health benefits.

CRediT authorship contribution statement

Shuo Zhang: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Samuel Stamp:** Investigation, Methodology, Supervision, Validation, Writing – review & editing. **Elizabeth Cooper:** Writing – review & editing, Conceptualization, Methodology, Validation. **Katherine Curran:** Conceptualization, Supervision, Validation, Writing – review & editing. **Dejan Mumovic:** Conceptualization, Project administration, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Shuo Zhang reports financial support was provided by EPSRC.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2023.110636.

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