Environmental Research 197 (2021) 111092

Contents lists available at ScienceDirect

Environmental Research

journal homepage: www.elsevier.com/locate/envres

Assessment of CO_2 and aerosol ($PM_{2.5}$, PM_{10}, UFP) concentrations during the reopening of schools in the COVID-19 pandemic: The case of a metropolitan area in Central-Southern Spain

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ARTICLE INFO

Keywords:
COVID-19 pandemic
Particulate matter
SARS-CoV-2 transmission risk mitigation
School environment
Ventilation conditions

ABSTRACT

Public health authorities have been paramount in guaranteeing that adequate fresh air ventilation is promoted in classrooms to avoid SARS-CoV-2 transmission in educational environments. In this work it was aimed to assess ventilation conditions (carbon dioxide, CO_2) and suspended particulate matter ($PM_{2.5}$, PM_{10} and UFP) levels in 19 classrooms – including preschool, primary and secondary education – located in the metropolitan area of Ciudad Real, Central-Southern Spain, during the school's reopening (from September 30th until October 27th, 2020) after about 7 months of lockdown due to COVID-19 pandemic. The classrooms that presented the worst indoor environmental conditions, according to the highest peak of concentration obtained, were particularly explored to identify the possible influencing factors and respective opportunities for improvement. Briefly, findings suggested that although ventilation promoted through opening windows and doors according to official recommendations is guaranteeing adequate ventilation conditions in most of the studied classrooms, thus minimizing the risk of SARS-CoV-2 airborne transmission, a total of 5 (26%) surveyed classrooms were found to exceed the recommended CO_2 concentration limit value (700 ppm). In general, preschool rooms were the educational environments that registered better ventilation conditions, while secondary classrooms exhibited the highest peak and average CO_2 concentrations. In turn, for $PM_{2.5}$, PM_{10} and UFP, the concentrations assessed in preschools were, on average about 2-fold greater than the levels obtained in both primary and secondary classrooms. In fact, the indoor $PM_{2.5}$ and PM_{10} concentrations substantially exceeded the recommended limits of 8hr-exposure, established by WHO, in 63% and 32% of the surveyed classrooms, respectively. Overall, it is expected that the findings presented in this study will assist the establishment of evidence-based measures (namely based on ensuring proper ventilation rates and air filtration) to mitigate preventable environmental harm in public school buildings, mainly at local and national levels.

1. Introduction

The causative pathogen of the COVID-19 outbreak has been identified as a highly infectious novel coronavirus referred as severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) with origin in Wuhan (December 2019) that continues to spread globally. On February 11th, the first two cases were confirmed in Spain. These were labelled as imported cases of infection, since they were related to contacts with confirmed cases of SARS-CoV-2 in Germany and France (ISCIII, 2020a). At that time, 44,554 cases were confirmed by the WHO (44,235 in China and 319 in the rest of the world - 37 in the European Union), including 910 deaths among the confirmed cases (908 in China and 1 outside of China) (ISCIII, 2020a). The first official death from COVID-19 reported in Spain occurred on February 13th and consisted of a 69-years-old man who previously travelled to Nepal (ISCIII, 2020b). Until October 28th, 2020, a total of 1,136,503 confirmed cases and 35,466 deaths have been

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https://doi.org/10.1016/j.envres.2021.111092
Received 13 January 2021; Received in revised form 25 February 2021; Accepted 24 March 2021
Available online 27 March 2021
0013-9351/

reported in Spain (MSCBS, 2020a).

A recent study estimated that the relative rate of COVID-19 death is substantially lower in people <65 years old than in older individuals (Ioannidis et al., 2020). Furthermore, a growing body of evidence shows that children and adolescents appear to present lower susceptibility to SARS-CoV-2 and are overall less severely affected than adults, particularly older patients (Götzinger et al., 2020; Viner et al., 2020). Nevertheless, there is some evidence suggesting that children are at similar risk of infection as the general population, though less likely to have severe symptoms (Bi et al., 2020). A study carried out in Madrid (Spain) from March 2nd to 16th, 2020, found that 60% of children with confirmed COVID-19 (25 out of 41) were hospitalized, 9.7% were admitted to the paediatric intensive care unit, and 9.7% needed respiratory support beyond nasal prongs (Tagarro et al., 2020). In fact, there is an ongoing discussion in the scientific community regarding the role of children and adolescents in the transmission and spread of SARS-CoV-2, with the real degree of asymptomatic transmission being unknown (Panovska-Griffiths et al., 2020; Verity et al., 2020; Yonker et al., 2020). Until October 28th, 2020, a total of 109,580 children up to 15 years (around 10% of the total confirmed cases) have been confirmed in Spain (ISCIII, 2020c).

Previous modelling studies have found that 5- to 19-year-olds are expected to suffer the highest-burden of respiratory infection during an initial spread, mainly due to their higher number of social contacts than adults, which has also been related to school settings (Mossong et al., 2008). WHO allied efforts with UNICEF and UNESCO and published a document that intended to help policymakers and educators with making decisions on running schools as safe as possible during the COVID-19 pandemic (WHO, 2020a). In this document, guidance to prevent the spread of SARS-COV-2 in educational settings, to be taken at both school and classrooms levels, includes environmental measures as i) "maintaining clean environment: frequent cleaning of surfaces and shared objects"; and ii) "ensuring adequate and appropriate ventilation with priority for increased fresh outdoor air by opening windows and doors". For instance, although sharing indoor space has been confirmed as a major risk factor in transmission of SARS-CoV-2 (Allen and Marr, 2020; Qian et al., 2020; Rodríguez-Barranco et al., 2021), enhanced ventilation may be a key element in limiting the spread of the SARS-CoV-2 virus and other infectious agents in enclosed environments (Li et al., 2007; Morawska et al., 2020).

Evidence is emerging indicating that, in addition to transmission via large droplets and fomites, SARS-CoV-2 is also transmitted via inhalation of aerosols (Allen and Marr, 2020; Miller et al., 2020). This recognition is critical for the establishment of effective strategies, namely based on indoor environmental quality (IEQ) improvement measures, for reducing the risk of airborne transmission that can be particularly potentiated in indoor environments (Allen and Marr, 2020; Zhang, 2020). In the last decade, a growing body of evidence has demonstrated that inadequate ventilation and poor indoor air quality (IAQ) conditions are very likely to occur in classrooms (Annesi-Maesano et al., 2012; Baloch et al., 2020; Fisk, 2017). Associations between the poor quality of the environment in classrooms and increased risk of development of diseases, including respiratory and allergic symptoms, and compromised academic performance in children have been well-documented (Baloch et al., 2020; Grineski et al., 2016). At this time, facing the COVID-19 developments and evidence addressed above, it is even more crucially important to properly tackle and address ventilation condition and IAQ status in educational environments. In this context, this work aimed to assess the comfort (temperature and relative humidity, RH) and ventilation conditions (based on CO_2 concentrations), and aerosol ($PM_{2.5}$, PM_{10} and UFP) concentrations in 19 classrooms from different educational environments (preschool, primary and secondary schools) during their reopening in the COVID-19 pandemic. All studied school buildings were located in the metropolitan area of Ciudad Real, Central-Southern Spain. It is expected that the obtained results will allow us to study the effectiveness of the currently adopted ventilation-related strategies, in promoting adequate IEQ conditions that minimize the risk of spreading of the SARS-CoV-2 in classrooms.

2. Methods

2.1. Description of the local context, study design, and surveyed educational buildings

The official date of closure for schools and Universities due to COVID-19 in Spain was March 16th, 2020 (March 13th in the region of Castilla La Mancha). To reopen safely, the contingency plan for schools implemented in Spain included very similar measures to those implemented in other European countries, in strict accordance with the existing WHO recommendation. This included the establishment of rigorous infection control practices, mainly by promoting frequent hand hygiene, making hand sanitizer available for all, guaranteeing appropriate and periodic cleaning of surfaces, maximizing physical distance to maintain at least 1.5 m distance (whenever possible), and increasing ventilation of the indoor spaces by opening windows and doors. Moreover, the use of face masks has been mandatory for the whole period while at school, indoors and outdoors, except for preschool children (JCCM, 2020a). Besides, the playground areas have been divided by courses to prevent close interaction between children from different classrooms/courses. Due to the recent evidence of SARS-CoV-2 transmission via aerosols, on November 18th' 2020, the Spanish Health Ministry published a document also recognizing this type of transmission in indoor environments, as schools, and presenting some measures to properly prevent it (MSCBS, 2020b).

A total of seven school buildings were surveyed in this study (Fig. 1). Five out of 7 were located in Ciudad Real, a small city from Spain in the centre of the Iberian Peninsula (38°59′N, 03°56′W) with around 75,000 inhabitants. The location of the other school was placed in the village of Poblete (38°56′N, 3°58′53″W), a rural area with 2600 inhabitants at approximately 8 Km South-West from Ciudad Real and surrounded of farm fields. The last one was in the semi-urban area of Miguelturra (39°2′ N, 3°55′W) at 6 Km South-East from Ciudad Real. According to the school calendar for the 2020/21 course in the region of Castilla La Mancha, the official date for reopening preschools, primary and secondary schools was September 9th, 2020 (JCCM, 2020b).

The range of educational environments surveyed in the 7 different schools covered 19 different classrooms: 6 preschools (3-6 years-old children), 7 primary (6-12 years-old children) and 6 secondary (12-18 years-old adolescents) classrooms. The following criteria were considered to select the classrooms in each school: classrooms with the most representative conditions (in terms of area/occupation) but with the poorest ventilation according to the criteria of school's principals, and classrooms with higher occupation during weekdays, located in different floor levels and with different orientations. In preschools, classrooms with children who do not use face masks were prioritized for sampling. In fact, in this study 2 to 4 classrooms per school were chosen for environmental assessment during the reopening of schools after almost 7 months from the declared state of alarm in Spain, due to the coronavirus crisis. The IEQ assessment plan designed for this study was carried out in the selected classrooms from September 30th until October 27th, 2020. The accumulated incidence in the epidemiological week of October 19–25th was 212.6 cases per 100,000 inhabitants in Spain and 205.9 in Castilla La Mancha (ISCIII, 2020c).

Continuous monitoring of environmental parameters was carried out during the full operating hours of a school day under representative conditions of occupancy and use of the classrooms surveyed. The assessment works typically started around 5–15 min before the students entered the classroom until just the end of the lectures or even 1 h after the children leave the classroom. The schools have different timetables; however, in general, preschools and primary schools operated in September from 9.00 to 13.00 h, and thereafter the teaching period was extended to 14 h. For secondary schools, the teaching hours ranged from

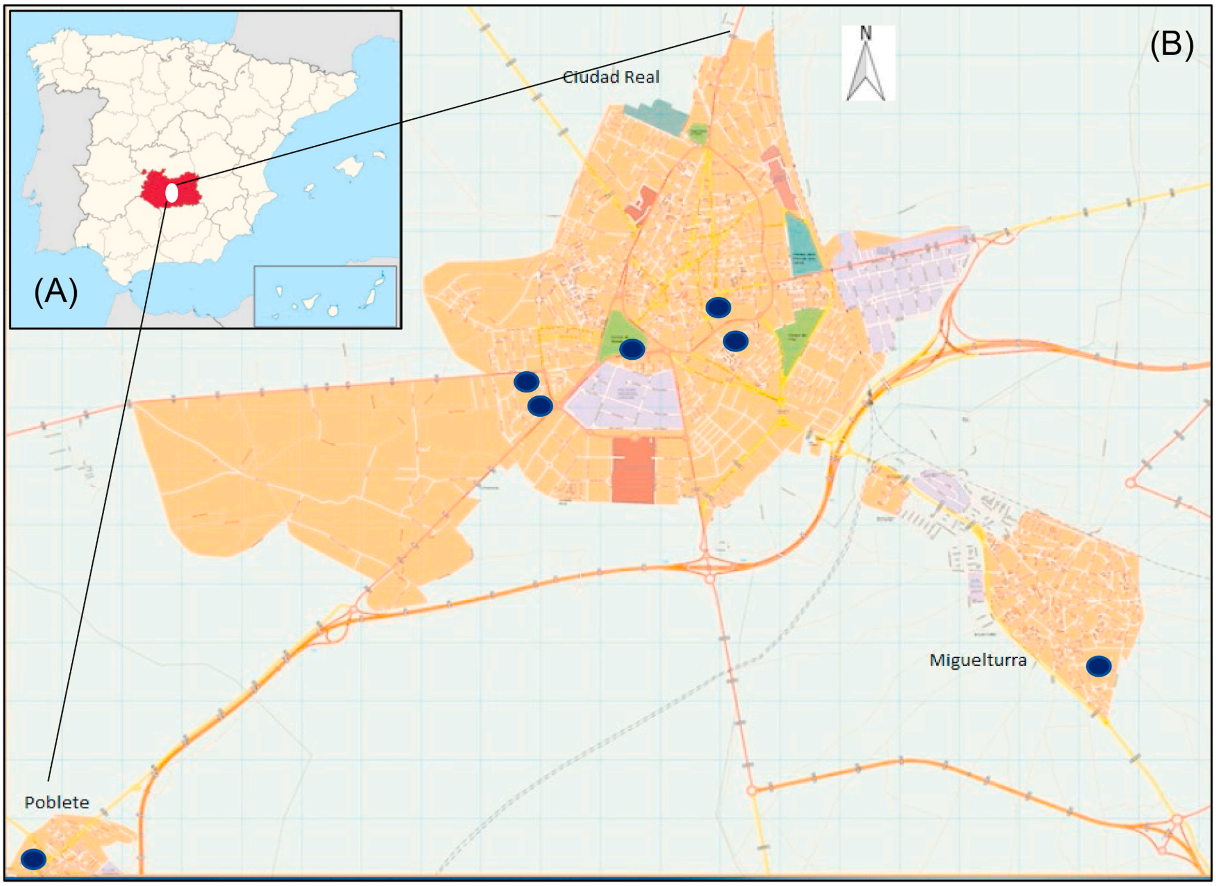

Fig. 1. Location of the metropolitan area of Ciudad Real (in the province of Ciudad Real in red) in Castilla la Mancha, Spain (A), and location of the surveyed school buildings (B). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

8.30 to 8.45 until 14.30–14.50 h. In all the cases, it included a break between teaching periods (period of non-occupancy of the classrooms) in the middle of the morning, which lasts approximately 30 min. Samplers/monitors were consistently placed at a height coinciding with the breathing zones of the pupils, maintaining a distance of at least 1.5 m from walls and 1 m from the pupils avoiding any direct disturbance by experienced researchers (WHO, 2020b).

2.2. Assessment of comfort and ventilation conditions

A portable data logger was used for measuring and logging CO_2, temperature and RH (model HD21ABE17, DeltaOHM, GHM Group, Germany). The measurement range and accuracy were the following: 0–5000 ppm, ± 50 ppm (+3 % of the reading), 1 ppm of resolution for CO_2 (NDIR dual wavelength sensor); −20 °C to 60 °C, ± 0.2 °C for temperature (NTC 10 kΩ sensor); and 0–100 %, ± 2% for humidity (capacitive sensor). Levels were measured based on the 1 min logging interval. The CO_2 outdoor concentration was checked every day before and after measuring in indoor air. The average ambient air temperature for the period of monitoring was obtained from AccuWeather, Inc. (http://www.accuweather.com/).

2.3. Measurement of airborne particulate matter levels

Airborne particulate matter ($PM_{2.5}$ and PM_{10}) concentrations were assessed using a DustTrak DRX aerosol monitor (model 8533, TSI, Inc., MN, USA) with a range of operation from 0.001 to 150 mg/m^3. Levels of ultrafine particles (UFP) were measured by a P-Trak portable condensation particle counter (model 8525, TSI, Inc., MN, USA) which is able to count airborne particles sizing from 0.02 to 1 μm at a concentration range from 0 to 5 × 10^5 particles/cm^3. All data loggers were programmed for a 1-min data logging interval and were operated in the field according to the manufacturer' recommendations. To minimize the impact of instrument drift on the measurement, all DustTrak and P-Trak monitors were auto-zeroed immediately before the monitoring work conducted in each indoor space surveyed. According to the manufacturer, both equipments had an accuracy of ±5%. In addition, all the equipment was calibrated within the 12 months preceding the present study.

3. Results and discussion

3.1. General characteristics of buildings and indoor spaces surveyed

The information collected through a checklist during the walk-through inspection on the characteristics of school buildings and indoor spaces surveyed is presented in Table 1. Briefly, for each classroom, the following information was collected: location of the room within the building (floor), number of children/occupancy, walls (surface materials), year of original building construction, floor covering materials, room dimensions, practices for promoting ventilation, kind of playground, the orientation of classroom (e.g., playground, main road, street-facing), and blackboard type. During the sampling campaign, the heating systems were switched off in all of the surveyed schools. All classrooms were found to comply with the recommendation on having windows and the door opened to favour the cross ventilation during the whole teaching period (natural ventilation). In fact, most of the sampled classrooms were exclusively naturally ventilated. Only one classroom was located in a new building built in 2019 with mechanical ventilation according to Spanish National Regulation (RITE, 2007). This classroom

Table 1
General characteristics of the 19 surveyed classrooms.

School	Classroom	Number of Children	Use of Mask	Floor	Age of the building	Number of Windows	Number of Doors	Orientation of classrooms	Area/ m^2	Floor covering	Walls	Type of Playground floor	Type of Board(s)	Outdoor Pollution source (s)
1	1-a Preschool	22	No	0	25	4	1[a]	Playground	50	Ceramic tile	Paint/ ceramic	Sand/trees	B + W	No
	1-b Primary	22	Yes	1	25	4	1[a]	Playground	45	Ceramic tile	Paint	Stones/trees	B + W	
	1-c Primary	20	Yes	0	1	4	1[a]	Playground	50	Ceramic tile	Paint	Sand and stones	B	
2	2-a Preschool	25	No	0	40	2	1[a]	Playground	45	Linoleum	Paint/ ceramic	Concrete	W	Traffic (main road)
	2-b Primary	26	Yes	1	40	2	1[a]	Playground	64	Ceramic tile	Paint/ ceramic	Concrete	E	
	2-c Secondary	27	Yes	2	40	2	1[a]	Playground	64	Ceramic tile	Paint/ ceramic	Concrete	B	
	2-d Secondary	23	Yes	2	40	4	1[a]	Playg./road	50	Ceramic tile	Paint/ ceramic	Concrete	W	
3	3-a Preschool	19	No	0	32	2[c]	2[a]	Street	58	Linoleum	Paint/wood	Sand	B + W	Traffic (main ring road)
	3-b Primary	23	Yes	2	32	1	2[a]	Street	63	Ceramic tile	Paint/cork	Concrete	B	
4	4-a Preschool	23	No	1	45	2	1[a]	Playground	33	Linoleum	Paint/ linoleum	Concrete	W	Traffic (main ring road)
	4-b Primary	28	Yes	2	45	3	1[a]	Playground	38	Ceramic tile	Paint/ ceramic/cork	Concrete	B	
	4-c Secondary	30	Yes	1	45	5	1[a]	Playground	51	Linoleum	Paint/ linoleum	Concrete	B	
	4-d Secondary	25	Yes	1	45	4	1[a]	Playground	62	Ceramic tile	Paint/ ceramic/cork	Concrete	B	
5	5-a Preschool	24	No	0	14	3	1[a] +1[b]	Playground	55	Linoleum	Cork	Soil and trees	B + E	Traffic (main ring road)
	5-b Primary	24	Yes	1	14	3	1[a]	Street	57	Ceramic tile	Paint/ ceramic	Soil and trees	B + W	
6	6-a Preschool	23	No	0	25	3	1[a] +1[b]	Street	49	Linoleum	Paint	Sand and ceramic	B	Street
	6-b Primary	22	Yes	1	25	3	2[a]	Street	44	Ceramic tile	Paint	Sand and ceramic	B	
7	7-a Secondary	24	Yes	0	26	4	1[a]	Playground	57	Ceramic tile	Paint	Concrete and garden	B	Traffic (intercity road)
	7-b Secondary	12	Yes	0	26	4	1[a]	Playground	57	Ceramic tile	Paint	Concrete and garden	B	

B, Blackboard; W, Whiteboard; E, Electronic/Interactive board.
[a] Doors in the classroom facing an indoor corridor.
[b] Doors facing outdoors.
[c] Balconies.

is expected to meet category IDA2 (12.5 L/s per person). In this single classroom, both natural and mechanical ventilation were used while the monitoring was conducted. Regarding cleaning routines reported in the sampled classrooms, all the surfaces were disinfected daily in the afternoon (after classes) using bleach and water; ventilation of classrooms was kept during cleaning procedures. Hallways and toilets were disinfected several times during the morning/teaching periods. According to the measured area and ceiling height, the classrooms that were evaluated had volumes that ranged from 99 to 219 m^3. The occupancy of the classrooms varied from 20 to 30, except one secondary classroom that applied a semi-presential regime having 12 students in the classroom. Thus, the occupation density was between 1.3 and 3 m^2/person (4.4 m^2/person for the semi-presential classroom).

The concentrations assessed in this work showed a considerable fluctuation across the classrooms surveyed as shown in Figure S1. The distribution of the concentration levels of the air parameters assessed in the indoor air of the different educational settings surveyed are also presented in Table 2, and will be extensively addressed below. The results will be particularly explored in light of the existing guidelines and threshold levels and literature, having as the main reference evidence from the European SINPHONIE project (*Schools Indoor Pollution and Health Observatory Network in Europe,* http://sinphonie.rec.org/) that covered 114 primary schools and about 340 classrooms (including some preschool classrooms) across 23 European countries (Spain not included).

3.2. Comfort and ventilation conditions

According to SINPHONIE guidelines, "physically comfortable operative temperatures in classrooms should be maintained, as far as possible, throughout the year according to the season and the external air temperature (between approximately 20 °C and 26 °C)" (Kephalopoulos et al., 2014). In agreement, the present study found very concordant temperatures in the surveyed classrooms that ranged, in average, from 19 to 21 °C (Table 2). In addition, the obtained maximum temperatures reached values between 24 and 27 °C, while sporadic minimum temperature values (between 12 and 17 °C) were only measured in the early morning, at the beginning of the school day, when the temperature outside was typically lower. According to AccuWeather records, for the periods of study, ambient air temperatures were in average 18.5 °C (range of average outdoor temperatures verified in the days of the survey: 11 to 26 °C). Regarding indoor RH, the average levels measured in all the classrooms were found to strictly comply with the recommended comfort level (42–50%). Absolute minimum and maximum RH values registered were 22 and 79%, respectively.

In regards to indoor CO_2 levels, which are widely used as a proxy for ventilation rates (Fisk, 2017), as shown in Table 2, preschools were the educational environments in which the lowest average CO_2 levels were obtained (553 ± 56 ppm). In turn, the highest average CO_2 concentration (699 ± 172 ppm) was obtained in the secondary classrooms. Although a limit of 1,000 ppm for CO_2 has been worldwide accepted according WHO recommendation (WHO Regional, 2000), for prevention of COVID-19 transmission in enclosed spaces, national and international recommendation refer that indoor CO_2 concentrations in classrooms should not exceed 700 ppm, 550 ppm in hallways (LIFTEC and CSIC, 2020; Marr et al., 2020). According to these documents, 700 ppm would indicate that 0.75% of the air in the room has already been breathed before by the occupants (LIFTEC and CSIC, 2020). This means that a higher % can represent a not negligible risk of airborne transmission in case of the existence of infected occupants. In this context, the average concentrations of CO_2 measured in a total of 5 (26%) surveyed classrooms exceeded the recommended limit: 2 from primary schools (up to 737 ppm, 2 buildings), and 3 in secondary schools (up to 941 ppm, 2 buildings). According to SINPHONIE guidelines (Kephalopoulos et al., 2014), promoting healthy ventilation conditions in schools requires that CO_2 concentrations above 1,500 ppm are not reached in classrooms. In this work, absolute maximum values above this limit were only obtained in 2 classrooms (both of them from secondary schools). For instance, the secondary classroom in which the highest average CO_2 concentration was obtained presented also the greatest maximum value obtained (2,117 ppm) that seems to be indicative of a very high air stuffiness settings in the respective classroom. Regarding the minimum reported values from the beginning until the end of lectures, very similar levels have been reported in all the educational environments studied (Table 2). The boxes shown in Figure S1a (Supplementary Materials) provide a detail view on the indoor concentration levels of CO_2 found in the surveyed preschool, primary and secondary classrooms.

Comparing CO_2 concentrations obtained in this work with those reported by past studies conducted elsewhere, it can be verified that the present ventilations conditions in the sample of classrooms surveyed are greatly better than those reported in most of the existing literature for similar indoor environments. In fact, CO_2 levels reported here were, on average, 2.6-fold lower than the reported from SINPHONIE European classrooms (Baloch et al., 2020). Furthermore, CO_2 concentrations were found to be greatly lower, even in comparison with concentrations reported for classrooms located in other regions of Spain (Fernández-Agüera et al., 2019; Krawczyk et al., 2016) or in countries with similar climate conditions, as Portugal (Madureira et al., 2016).

Overall, findings presented in this section suggest that the fresh air classrooms' ventilation promoted through open windows and doors during the reopening of schools is guaranteeing adequate ventilation rates (in terms of indoor levels CO_2) in about 74% of the studied classrooms, and thus in minimizing the risk of SARS-CoV-2 airborne transmission. Noteworthy, results also showed that adequate fresh air ventilation was achieved without representing an apparent concern in terms of hygrothermal comfort for the children. In fact, for the period of the assessments, very warm ambient temperatures were registered in the geographical area of study. Nevertheless, because it can be anticipated that the conditions are likely to suffer significant changes in colder months of winter as, based on the typology of practiced ventilation, compliance with adequate ventilation rates often causes complaints related to issues with thermal comfort, two additional sampling campaigns in the same sample of classrooms are already being planned for a

Table 2
Summary statistics obtained for the measured parameters in the pre, primary and secondary classrooms surveyed (19 different classrooms in 7 different schools).

Preschools (n = 6, 6 classrooms)*	**Median**	**Average (SD)**	**Min – Max**
Temperature, °C	21.2	20.8 (2.0)	15–24
RH, %	43.0	45.0 (10.5)	26–67
CO_2, ppm	539.0	553.0 (56.0)	391–1,075
$PM_{2.5}$, µg/m^3	41.0	48.0 (26.0)	6–364
PM_{10}, µg/m^3	64.0	81.0 (55.0)	8–749
UFP, pt/cm^3	7,022	13,338 (8.1)	1,714–115,916
Primary (n = 6, 7 classrooms)*	**Median**	**Average (SD)**	**Min–Max**
Temperature, °C	21.0	20.6 (1.3)	17–25
RH, %	48.0	50.3 (13.2)	26–79
CO_2, ppm	565.0	602 (109.0)	379–1,341
$PM_{2.5}$, µg/m^3	26.0	25.0 (8.0)	1–105
PM_{10}, µg/m^3	41.0	38.0 (11.0)	2–141
UFP, pt/cm^3	6,600	6,880 (4,382)	185–67,053
Secondary (n = 3, 6 classrooms)*	**Median**	**Average (SD)**	**Min–Max**
Temperature, °C	18.7	18.8 (3.5)	12–27
RH, %	45.1	42.0 (10.1)	22–63
CO_2, ppm	661.0	699.0 (172.0)	393–2,117
$PM_{2.5}$, µg/m^3	22.0	27.0 (13.0)	5–279
PM_{10}, µg/m^3	33.0	40.0 (18.0)	6–490
UFP, pt/cm^3	6,490	6,951 (3,361)	997–29,348

*n=(number of different surveyed school buildings, number of classrooms).
Min – Max, correspond to the maximum and minimum absolute values that were measured, SD, standard deviation.

near future.

3.3. Airborne particulate matter ($PM_{2.5}$, PM_{10} and UFP)

In addition to ventilation, air quality was also evaluated in the surveyed classrooms, in terms of aerosols levels, due to 4 main reasons:

i) the negative health impacts that have been associated to particulate matter, in particular to those fractions of smaller sizes, i.e. $PM_{2.5}$ and UFP (Lavigne et al., 2019; Stone et al., 2017; WHO, 2006);
ii) SINPHONIE results demonstrating that unhealthy levels of PM are very likely to occur in naturally ventilated schools (Baloch et al., 2020);
iii) the emerging evidence hypothesizing that health outcomes of COVID-19 are aggravated by poor air quality, in particular by exposure to $PM_{2.5}$ (Pozzer et al., 2020);
iv) the existence of some reports referring a putative transmission pathway for SARS-CoV-2 through aerosols namely by surface deposition of the virus and resuspension from the surfaces (Liu et al., 2020).

Descriptive statistics of the $PM_{2.5}$, PM_{10} and UFP levels assessed in the 19 classrooms are summarized in Table 2. Furthermore, Figure S1b, S1c and S1d (Supplementary Materials) provide a detail view of the indoor concentration levels of $PM_{2.5}$, PM_{10} and UFP found in all classrooms. Although the concentrations of airborne particles measured for the classrooms were spread out over a wide range of values, for all the particle size fractions that were measured, the highest average, median and maximum values were consistently obtained for preschools rooms. In fact, for $PM_{2.5}$, PM_{10} and UFP the average concentrations found in preschools, were about 2-fold greater than the average levels found in classrooms from primary and secondary schools. A similar outcome was observed for the respective indoor median values.

The average concentrations of $PM_{2.5}$ obtained in 12 of the 19 surveyed classrooms, exceeded the recommended limit of 25 μg/m^3 for 8hr-exposure, established by WHO (WHO, 2006): 5 preschools (up to 96 μg/m^3), 4 primary (up to 32 μg/m^3), and 3 secondary classrooms (up to 42 μg/m^3). In the case of PM_{10}, 6 surveyed classrooms exceeded the 50 μg/m^3 recommended by WHO guidelines (WHO, 2006): 4 preschools (up to 186 μg/m^3), and 2 secondary schools (up to 63 μg/m^3). Although the high percentage of classrooms that were found to fail for the compliance of healthy PM concentration according to WHO guidelines, these findings are in line with SINPHONIE results, in which the average $PM_{2.5}$ concentrations found in European classrooms were similar to those found in this work for preschools. However, $PM_{2.5}$ reported in SINPHONIE project (Baloch et al., 2020) were substantially higher than the obtained for primary and secondary classrooms surveyed in this work. In addition, because SINPHONIE outcomes also showed that children exposed to higher $PM_{2.5}$ concentrations were found to be at increased risk of suffering from airways disorders (Baloch et al., 2020), strategies for reducing indoor levels in classrooms need to be critically addressed, in order to achieve healthy educational environments for children.

Regarding UFP, due to the lack of existing guidelines or threshold values, no considerations about the putative risk that the assessed UFP levels can constitute to health of children can be established. In the single study (as far as we know) conducted in Spain, concretely in Barcelona, that assessed UFP concentration in schools environments found a median value (15,376 pt/cm^3) expressively higher than the obtained in this survey (Rivas et al., 2014). In fact, the median values obtained for indoor UFP levels (6,490 to 7,022 pt/cm^3, Table 2) were also slightly lower than the median number concentrations measured in a sample of Portuguese primary schools (n = 20; 7,798 pt/cm^3) (Slezakova et al., 2019). In the Portuguese survey, the median UFP levels among classrooms ranged from 1,560 to 16,780 pt/cm^3 by comparison with 292–21,960 pt/cm^3 in the present work. In addition, the average UFP concentration number found in the preschools (13,338 pt/cm^3) were very similar to those reported for outdoor environment of the same geographical region, in a study conducted in Ciudad Real in 2013 that obtained average UFP levels of 11,000 pt/cm^3 (Aranda et al., 2015).

In accordance with the growing body of evidence suggesting that ambient particles concentrations have a major contribution to the PM concentration found in indoor environment (Slezakova et al., 2019), the natural ventilation through opened windows and doors - which has been mandatory following the health authorities' recommendations - are very likely to be influencing the high $PM_{2.5}$, PM_{10} and UFP levels reported in the surveyed classrooms. In fact, the highest aerosols concentrations found in preschools is very likely to result from the fact that most (5 out 6) of the audited preschool classrooms were located on the ground floor while the primary and secondary were typically located in upper floors (1st or 2nd floors, primary: 6 out of 7; secondary: 4 out of 6). This is in accordance with the study carried out by Slezakova et al. who reported UFP levels in rooms situated on the ground floor significantly higher than those placed on the upper floors (Slezakova et al., 2019). Although the real contribution from outdoor sources cannot be accurately estimated due to the lack of measurements in the outdoor environment, the location of preschools classrooms on the ground floor seems to promote a stronger infiltration of polluted outdoor air.

3.4. Worst case scenarios: classrooms exhibiting maximum peak concentrations

The classrooms that presented the worst indoor environmental conditions, according to the peak concentration obtained for CO_2, $PM_{2.5}$, PM_{10} and UFP, were selected to be particularly explored in order to evaluate temporal dynamics and attempt to identify causes and opportunities for improvement.

3.4.1. Classroom exhibiting peak CO_2 concentrations

Fig. 2a shows the evolution of CO_2 levels throughout the school day (from 9 until 14.45 h, local time) of the surveyed classroom that exhibited the highest maximum CO_2 concentrations (2117 ppm); this room, which is situated in a secondary school, also presented the highest average CO_2 concentration of the present study (941 ppm). A total of 28 occupants (27 students + the teacher) were in the classroom during the monitoring. On the day of the study, this classroom presented CO_2 concentrations that were mostly in the range of 800–1,000 ppm, from the beginning of the school day (at 9 h) to about 13 h. During the 30 min-break period (around 11.45–12.15 h), the CO_2 concentrations decreased to values below the recommended limit (Fig. 2a); at the time of the occupants return, after the break, the CO_2 levels rapidly increased possibly, because during the breaking period, they had been playing, practicing sports, running, etc. (this is a common effect observed in all the surveyed classrooms). In particular, the measured concentrations of CO_2 were found to steadily increase from 13 h until the end of the lectures at 14.45 h, when the maximum value was reached. The temperature in this classroom also increased slight and continuously from 21.6 to 26.7 °C from the beginning of the lectures, being this last temperature, the maximum registered in the present study. Notwithstanding, this temperature increase from the beginning until the end of the lectures was also observed in all the studied classrooms. Concurrent to the observed temperature increment throughout the teaching period, the RH levels were slightly decreasing but all the readings were in compliance with recommended ranges.

Regarding the classroom's geometry (Fig. 2b), it consists of a rectangular room of 64 m^2, being one of the largest classrooms that were studied. This room is located on the 2nd floor of the school building with windows and door facing each other, both located on the smaller sides of the rectangle (thus not representing a long extension of windows). The windows (only two) and the door were opened during the whole period of the lectures for promoting continuous natural ventilation to the

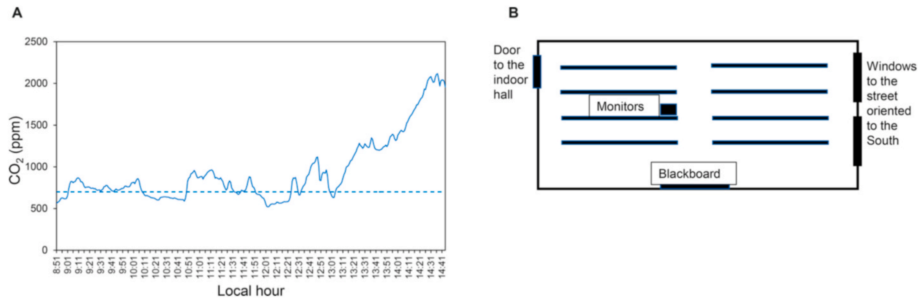

Fig. 2. **(a)** Evolution of CO_2 levels in the classroom with the maximum peak and average CO_2 concentrations obtained in the study (measured from the beginning of the lectures at 9 h until the end at 14.45 h (local time) on October 9th, 2020). The dashed line corresponds to the threshold of 700 ppm from national recommendations. (**b**) Diagram of the classroom showing the location of openings for ventilation purposes and of the monitors for CO_2 and particulate matter assessment.

indoor space. The windows open to the outdoor playground area and the door onto an indoor hallway with a window to outdoors. Although this distribution of facing doors and windows is likely to favour cross ventilation (described as the best natural ventilation approach, in the absence of forced mechanical ventilation), obtained CO_2 concentrations suggest that this does not seem to be enough for providing adequate ventilation rate, at the existing occupancy. Nevertheless, because the classroom's windows are oriented to the South exposed to solar radiation, the possible use of the external sunblinds to reduce the sun exposure from 13.00 to 14.45 h cannot be excluded. This could substantially reduce the effectiveness of renewed air and justify the measured CO_2 concentration peak. In addition, this can be also partially justified by an inefficient cross-ventilation induced by the fact that the door does not lead directly to the street but to an indoor hallway.

Considering the particulate matter concentrations obtained in this classroom (data not shown) the high peak concentrations were observed at the students' entrance at about 9 h (UFP: 26,598 pt/cm^3; $PM_{2.5}$: 80 μg/m^3; PM_{10}: 138 μg/m^3), which rapidly decreased around 20–30 min. For $PM_{2.5}$ and PM_{10} this descent was situated in values around, or slightly above the WHO limit values. The reported averages were 10,000 pt/cm^3, 41 μg/m^3 and 53 μg/m^3, for UFP, $PM_{2.5}$ and PM_{10}, respectively. These results show that this classroom needed to be marked for urgent intervention that should include actions for implementing proper ventilation rates and effective PM source control and/or air filtration-based measures.

3.4.2. Classroom exhibiting peak particulate matter concentrations

Fig. 3a represents the evolution of UFP in the classroom in which the maximum (115,916 pt/cm^3) and average (26,112 pt/cm^3) levels were obtained. The geometry of the respective room and the position of windows and door are represented in Fig. 3b. This is a preschool classroom situated on the ground floor of the building with an occupation that included 22 pupils and the teacher. A good ventilation is achieved in this classroom with CO_2 levels around 600–800 ppm all the time. The RH ranged 30–40% and the temperatures of 21–24 °C (data not shown). As it can be seen in Fig. 3a, the UFP peak levels were obtained at the moment of the entrance of the pupils in the room around 9.00 h. It takes around an hour for the levels to drop to a value of approximately 10,000 pt/cm^3. During the period of the mid-morning break (from 11.30 to 12.00 h) there was a noticeable increment (more than 2-fold) in UFP levels concomitant to the recreational activities of the children in outdoor environment. In fact, the windows of this room, which were opened during the whole monitoring period, are faced to an outdoor area that included a sand playground where pupils typically play during the mid-morning break, but also before the beginning and after the end of the lectures. The UFP levels remained above or around 20,000 pt/cm^3 after the return of children to the classroom until the end of the lessons at 13.00 h. The preschool children left the room at about 13.00 h, but many of them stayed in the school building a bit more for playing in the playground while they waited for their tutors. After this hour, the indoor airborne UFP number concentration rise rapidly to >50,000 pt/cm^3. The observed dynamics of the measured UFP levels in association to the outdoor activities of the preschool, suggests the existence of infiltration of a substantial number of UFP that are resuspended by the activities of the pupils in the sand throughout the long extension of windows facing the playground. In addition, since the higher UFP concentrations number were obtained at the beginning and the end of school hours that correspond to the rush hours of movement of people and traffic in the school' surrounding outdoor environment, emissions from motorized transports, mainly due to the children transportation by their tutors, are likely to have a great contribution to the observed levels.

Because there is a growing body of evidence showing irrefutable associations between exposure to UFP and detrimental impacts on human health, namely respiratory, cardiovascular, genotoxic/carcinogenic effects (Lavigne et al., 2019; Seaton et al., 1995; Stone et al., 2017), to adopt proper measures to reduce UFP levels in the classrooms it is paramount to protect pupils and teachers' health. In this particular case, it is recommended to consider the restructuring of the existing outdoor playground, not only because sand playground appeared to be a source of UFP but also because it has been described that it can act as

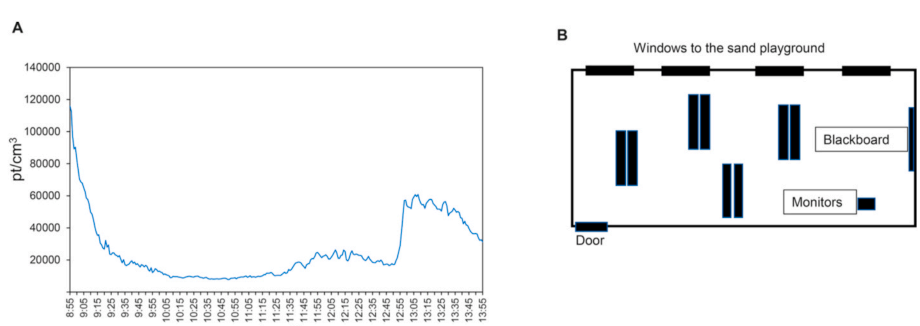

Fig. 3. **(a)** Evolution of UFP number concentrations in the classroom with the maximum peak and average UFP levels obtained in the study (Measured from 9 until 14 h, local time, on September 30th, 2020). **(b)** Diagram showing the geometry of the room with windows opened into the sand playground.

reservoir of pathogens and constitute a relevant health risk for children (Orden et al., 2018; Staff et al., 2012).

In this specific case the preschool classroom was also the one that presented the highest airborne $PM_{2.5}$ and PM_{10} obtained in this study: average of 96 and 186 μg/m^3, and maximum levels of 364 and 749 μg/m^3 for $PM_{2.5}$ and PM_{10}, respectively. Fig. 4 shows the variability of $PM_{2.5}$ and PM_{10} concentrations throughout the school day. As it can be observed in the graphic, the assessed airborne concentration of $PM_{2.5}$ and PM_{10} exceeded the respective recommended limit values during the whole occupancy period of the classroom (from 9.00 to 13.00 h). High levels of both $PM_{2.5}$ and PM_{10}, around 100 μg/m^3 and above 100 μg/m^3 respectively, were measured when pupils arrived at the room, at 9.00. But it was from 11.30 until 13.00 h that a stunning increase in the $PM_{2.5}$ and PM_{10} levels was observed, reaching very high peak values registered. The period of the mid-morning break is from 11.30 to 12.00 h, and as above-mentioned for assessed UFP levels, outdoor events are likely to have a substantial contribution to the indoor particle matter concentrations. Nevertheless, the real contribution from outdoor sources cannot be accurately estimated due to the lack of measurements of PM in the outdoor environment, and thus, contribution from emissions occurring in the indoor space cannot be also excluded.

In fact, for the COVID-19 context, in which classroom's windows are opened all day round, outdoor ambient pollution is very likely to play a greater contribution to indoor air pollution than that observed in pre-COVID-19 studies. In this study, the measurement of aerosols was only conducted indoors due to lack of equipment availability for simultaneous assessment in both indoor and outdoor spaces. The lack of data for outdoor concentrations significantly limits the ascertainment of the real contribution of ambient air pollution in the overall classrooms' IAQ. Further studies assessing levels of aerosols in both indoor and outdoor environments taking also into consideration meteorological-related factors (e.g. local dominant winds) need to be planned in order to accurately investigate the existence of significant associations.

4. Conclusion

Results from this work show that although the ventilation conditions assessed in the surveyed classrooms were found to be substantially improved compared to most of the existing (pre-COVID-19) reports for natural ventilated European classrooms, indoor CO_2 concentrations that exceeded the recommended limit of 700 ppm were found in 26% of the classrooms. In fact, for the period of the assessments, the strict implementation of the official recommendation on maintaining the windows and doors opened during whole school day to promote renewed indoor air renovation through natural ventilation did not seem to compromise comfort conditions (in terms of air temperature and RH) in the classrooms. However, further measurements are being conducted to cover an extended period of assessment that will include colder days of the winter season for assessing thermal-related issues as well as for collecting more comprehensive IEQ data that will allow to obtain more informative statistical data. Among the educational environments assessed, secondary classrooms presented, in general, worst ventilation conditions. In turn, preschools were the educational environments with higher air pollution levels by particulate matter.

The observed variation of IEQ conditions across classrooms can be an additional complication for ensuring safe and healthy conditions for children, teacher and staff at school. The establishment of IEQ control will be crucial for an accurate prioritization of risky cases for intervention. Indeed, according to the main findings of this work to properly explore strategies for ensuring adequate ventilation and air filtration levels will be essential in providing equal opportunities for children to continue learning in safe environments, during the pandemic and beyond.

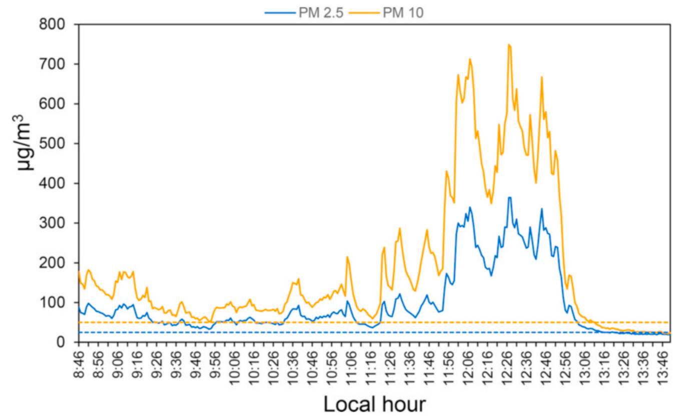

Fig. 4. Evolution of $PM_{2.5}$ and PM_{10} in the classroom with the maximum peak and average particulate matter levels obtained in the study. (Measured from 9 h until 14 h, local time, on September 30th, 2020). The dashed lines correspond to the threshold of 25 and 50 μg/m^3 recommended by the WHO guidelines for $PM_{2.5}$ and PM_{10}, respectively (WHO, 2006).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors gratefully thank the Junta de Comunidades de Castilla-La Mancha (Project SBPLY/17/180501/000522) for the financial support of this research work. We would also like to thank the support of principals, teachers and students from the schools that took part in the study: Ferroviario, Santo Tomás, Nuestra Señora del Prado, Santo Tomás de Villanueva, La Alameda, Campo de Calatrava and Alcalde José Maestro.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2021.111092.

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