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Environmental Research 202 (2021) 111560

Contents lists available at ScienceDirect

Environmental Research

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

CO_2 concentration monitoring inside educational buildings as a strategic tool to reduce the risk of Sars-CoV-2 airborne transmission

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ARTICLE INFO

Keywords:
CO_2
COVID-19
SARS-CoV-2 transmission risk mitigation
Indoor ventilation conditions
School re-opening
NDIR sensor

ABSTRACT

In order to avoid SARS-CoV-2 transmission inside educational buildings and promote the safe reopening of schools, the Italian Government, in line with the other European countries and in accordance with the WHO recommendations, adopted a contingency plan including actions able to guarantee adequate air ventilation in classrooms. Therefore, in this pilot study, a surveillance activity based on the real-time monitoring of CO_2 levels as a proxy of SARS-CoV-2 transmission risk, was conducted inside 9 schools (11 classrooms) located in Apulia Region (South of Italy) during the reopening of schools after the lockdown due to COVID-19 pandemic. More specifically, monitoring activities and data treatment were conducted to evaluate the initial scenario inside the classrooms (first stage of evaluation) and the potential improvements obtained by applying a detailed operating protocol of air ventilation based on specific actions and the simultaneous real time visualization of CO_2 levels by non-dispersive infrared (NDIR) sensors (second stage of evaluation). Although, during the first evaluation stage, air ventilation through the opening of windows and doors was guaranteed, 6 (54%) classrooms showed mean values of CO_2 higher than 1000 ppm and all classrooms exceeded the recommended CO_2 concentration limit value of 700 ppm. The development and implementation of tailored ventilation protocol including the real time visualization of CO_2 levels allowed to depict better scenariosAn overall improvement of CO_2 levels was indeed registered for all classrooms where teachers were compliant and helpful in the management of the air ventilation strategy. Therefore, this study reports the first evidence-based measures demonstrating that, with the exception of few environments affected by structural limits, the real-time visualization and monitoring of CO2 concentrations allowes effective air exchanges to be implemented and contributes to prevent SARS-CoV-2 transmission. Moreover, on the basis of the monitoring outcomes and in order to ensure adequate air ventilation in educational buildings, a 4 level-risk classification including specific corrective actions for each level was provided.

1. Introduction

The Severe Acute Respiratory Syndrome Coronavirus-2 (SARS-CoV-2) is the responsible agent of the COVID-19 pandemic declared by March 2020 by the World Health Organization. Starting as an epidemic event in the city of Wuhan (China) in the late December 2019, it evolved as a global outbreak worldwide counting at April 2021 about 148,480,035 confirmed COVID-19 cases and 3,134,615 deaths. Nowadays, interdisciplinary approach-based scientific research aims to deepen the factors underlying the routes of transmission of SARS-CoV-2 in order to minimize its spread. The existing theories speculate on three main viral transmission pathways: a) transmission by exhaled droplets; b) airborne transmission by virus-containing aerosol and c) transmission via fomites through the direct contact with contaminated surfaces (WHO, 2020). The viral transmission via virus-laden droplets is a well-established transmission pathway based on the transfer of larger respiratory

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https://doi.org/10.1016/j.envres.2021.111560
Received 28 April 2021; Received in revised form 16 June 2021; Accepted 16 June 2021
Available online 3 July 2021
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droplets (with diameter ranging from 5 to 20 μm) from one infected subject to other subjects at close proximity through coughing, sneezing or speaking (Curtius et al., 2021; Drossinos and Stilianakis, 2020; Vuorinen et al., 2020; Gralton et al., 2011). Instead, the significance of the airborne transmission of SARS-CoV-2 through the exhalation of small microdroplets (also commonly referred to as 'aerosols') has been the object of an extensive discussion within the International scientific community over the pandemic emergency. At this regard, recently published studies based on investigations and modelling simulations under different indoor scenarios (restaurants, hospital wards) supported the hypothesis that small microdroplets with viral loads may travel indoors covering distances up to 10 m from the exhalation point thus activating aerosol SARS-CoV-2 transmission (Barbieri et al., 2021; Buonanno et al., 2020a; Lednicky et al., 2020; Li et al., 2020; Miller et al., 2021; Moraska et al., 2020). Indeed, unlike larger respiratory droplets that after being exhaled quickly fall onto the ground within few meters, the expired aerosol (microdroplets dimension less than 5 μm) may remain suspended into the air over longer periods of time, especially inside crowded and inadequately ventilated indoor spaces. The estimation of the relative contributions of the different transmission pathways (via droplets, via aerosol and via fomites) is a crucial point mainly in the view of the implementation of effective containment strategies in indoor environments where the airborne diffusion could reasonably occur at a distance greater than 2 m (6 feet) (Jayaweera et al., 2020; Marr et al., 2020; Setti et al., 2020). The containment measures for SARS-CoV-2 transmission, indeed, pose a substantial challenge inside enclosed environments when people gather and stay in close contact such as classrooms, shared offices, meeting rooms, restaurants, bars, etc. With specific regard to the educational buildings, the safely management of students inside classrooms has been extensively debated over the last year taking into account that both students and teachers share the same space for at least 5 h a day. Moreover, due to the need for maintaining thermal comfort during the winter season and for limiting the external noises, classrooms are often isolated and it's reasonable to assume that, especially in absence of a mechanical ventilation system, the air cannot be adequately renewed. This represents a critical issue in the COVID-19 pandemic era. Inside unvented or insufficiently vented classrooms, indeed, an infected asymptomatic teacher or student could spread a virus-containing aerosol inside classrooms just breathing and talking. Simulations by Beggs et al. (2020) showed that an infected speaking person in an office can lead to levels of virus-containing aerosols able to cause an infection in other people breathing the air in the same room. Mikhailov et al. (2004) in fact, demonstrated that in condition of relative humidity far below 100%, droplets emitted during speaking quickly lose their water content and much smaller droplet cores with sizes below about 10 μm remain airborne for minutes to hours and thus, they can diffuse by thermal convection, turbulence and other air movements and accumulate in a closed room. On the basis of these evidences, WHO published the guidelines to help policy makers on running schools as safely as possible during the COVID-19 pandemic (WHO, 2020a). More specifically, guidance suggests maintaining a clean environment by disinfection of surfaces and shared objects and ensuring effective ventilation by frequently opening windows and doors. In fact, enhanced ventilation may be a key element to face the spread of the SARS-CoV-2 virus in enclosed environments, especially, in a densely seated classroom. In the last decade, a growing number of studies have demonstrated that inadequate ventilation conditions and poor indoor air quality (IAQ) are very likely to occur in classrooms (Baloch et al., 2020; Di Gilio et al., 2017; Annesi-Maesano et al., 2012; de Gennaro et al., 2013, 2014, 2015, 2014). In fact, most schools are not equipped with pre-installed Heating, Ventilation and Air Conditioning systems (HVAC) and thus, venting is usually done by opening the windows during the breaks. In the same way, air cleaner systems such as electronic ones (e.g. ionizers, hydroxyl generators and electrostatic precipitators), ozone generating systems and filtering systems based on High Efficiency Particulate Air (HEPA) filters, are not usually present in schools (EPA, 2018; Afshari et al., 2020; https://www.scopus.com/authid/detail.uri?authorId=57219649415&eid=2-s2.0-85094613078Cheek et al., 2021). Moreover, even if the opening of windows and doors is often the only effective strategy to vent the classroom with outside fresh air, sometimes it is not possible due to cold temperature and heating costs. Anyway, the room ventilation remains a crucial point to reduce the risk of Sars-CoV-2 airborne transmission. In fact, on the basis of the Wells-Riley model (Riley et al., 1978) and in order to describe the spread of airborne pathogens such as tuberculosis, measles, influenza, H1N1, coronavirus (SARSCoV) (Noakes et al., 2006; Liao et al., 2005; Nicas et al., 2005; Beggs et al., 2003; Rudnick and Milton, 2003) and the more recent coronavirus (SARS-CoV-2) (Miller et al., 2020; Buonanno et al., 2020; Riediker and Monn, 2021; de Oliviera et al., 2021), some researchers developed theoretical models of airborne disease transmission in closed and well-mixed spaces. All these models are based on the assumptions that the emission of virus-carrying aerosols depends on: a) the number of people in shared indoor spaces; b) the wearing a well-fitted mask and c) indoor activities (speaking quietly or shouting; physical activities; etc) while, the rate of infection is inversely proportional to the room's ventilation outflow rate (Zhu et al., 2020). These models stress the need for air change through ventilation to reduce the risk of disease transmission in indoors environments and they have led to draw up several guidelines to reduce transmission risk (Allen et al., 2020; Minguillón et al., 2020). More specifically, in addition to social distancing and mask wearing, the indoor CO_2 monitoring is suggested as practical proxy of the transmission risk of respiratory infectious disease. Indeed, in indoor environments an excess of CO_2 is usually due to human exhalation and an increase of CO_2 levels over outdoor levels could be related to the increased probability to inhale breath exhaled by other people and thus, to infection risk (Rudnick and Milton, 2003; Peng and Himenez, 2021). Moreover, as reported by Peng and Himenez (2021), the volume mixing ratio of the excess CO_2 that an uninfected individual inhales for 1 h in an environment is a good indicator of the risk and it can be easily and directly monitored by considering indoor CO_2 concentration reading (usually in ppm) of a low-cost sensor. To date, several low-cost non dispersive infrared (NDIR) sensors have been used to monitor indoor CO_2 concentrations. These sensors provide data with high temporal resolution and allow their real time visualization onto a screen. Moreover, thanks to IOT technology several devices connected to the same hub or gateway, can share the data that they simultaneously collect. Therefore, these sensors result to be strategic tools for indoor CO_2 monitoring and SARS-CoV-2 transmission risk assessment especially inside environment where several subjects spend many hours a day.. At this regard, in this study NDIR sensors and the specific guide lines for indoor ventilation have been provided to eleven classrooms of nine schools in the Apulia region (South of Italy) in order to assess the SARS-CoV-2 transmission risk and to evaluate possible mitigation strategies. More specifically, the study aimed to identify the best practices for an effective natural air exchange in indoor environments and to evaluate both structural and operative factors that may limit it, identifying classrooms where the only protocols for natural ventilation are required and classrooms where mechanical and forced ventilation should be implemented.

2. Materials and methods

2.1. Classrooms surveyed in the study: description of general characteristics and scheduled activities

The surveillance activity inside the educational buildings was performed in the framework of a joint collaboration between the research group of Laboratory of Environmental Sustainability at the Department of Biology of University of Bari (Italy) and the Italian Society of Environmental Medicine. The technological support for the successful implementation of the pilot study was provided by a leading enterprise

in the development of innovative sensors and IoT technology for airborne pollutants monitoring. A total of nine school buildings located in each province of the Apulia Region in the South of Italy were then enrolled in the present study. Eleven classrooms differentiated for educational level were monitored: 2 pre-school (3–6 years old children), 5 primary (6–11 years old pupils) and 4 first-level secondary classrooms (11–13 years old students). The monitoring activity was performed at each location for three consecutive weeks starting from 18th January to February 8, 2021. The selection of the educational buildings (number and typology) followed a preliminary screening based on the expression of interest to be involved in the surveillance study provided by the schools on the regional territory and on the evaluation of the main characteristics of the schools (geographical position, educational level) to guarantee as much as possible the representativeness at regional scale. The main structural characteristics of the selected classrooms such as floor surface (m^2), volume (m^3), number of windows and typology of air ventilation are summarised in Table 1. Additional information on classroom educational level, daytime timetable and number of children/students present during the monitoring activity are also listed.

None of the selected educational buildings is equipped with a mechanical ventilation system able to ensure constant indoor air exchange rates. Therefore, all classrooms are naturally ventilated through the opening of the available doors and windows and the time and frequency of the opening/closing of doors and windows are generally decided by the teachers and are not scheduled. This can be partly related to the years of building construction (approximately between the 80's and 90's for all the selected schools) when the implementation of mechanical heating and ventilation systems was not contemplated yet within the construction planning. The thermal comfort during the winter time is guaranteed at all the investigated locations by the scheduled functioning of radiators (2 or more units depending on the room size). Over the monitoring period the pre-school classroom sessions were scheduled at 8:30 a.m. till 13:30 p.m. Timetables for primary classrooms, instead, ranged from 8:00–8:30 a.m. to 12:40–13:30 p.m. with the only exception of classroom 1b characterized by full-time daily sessions (08:00 a.m.-16:00 p.m.). Similarly, teaching hours for the selected secondary classrooms started at 08:00–08:30 a.m. till 13:00–13:30 p.m. except for classroom 5a with full-time school hours from 08:20 a.m. to 16:40 p.m. Timetables for both pre-school and full-time classrooms included an extended break for lunch while one break of 15–20 min in the middle of the morning was scheduled in all the classrooms regardless of the educational level. The present research activity was carried out one year after the worldwide pandemic emergency officially declared by the WHO in March 2020. The Italian Government, in line with the other European countries and in accordance with the WHO recommendations, adopted a contingency plan for the safe reopening of the educational buildings. School administrators and employees were asked to strictly implement a list of precautionary measures for hygiene control and infection prevention. As a result, during the monitoring activity, the hygiene inside the selected classrooms was generally promoted by the periodic use of hand sanitizer and the cleaning of surfaces. The infection risk was also significantly reduced by the use of face masks for the entire duration of the lessons (the use was mandatory for both students and teachers with the only exception of the pre-school children) and guaranteeing the maximum distance among the students through a proper spatial distribution of seats inside the classrooms.

3. Description of the experimental design

The experimental design has been developed based on a two-stage evaluation approach. The first two-three days of the monitoring activity inside each classroom were intentionally dedicated to a preliminary evaluation addressed to trace CO_2 daily concentration pattern. This first level evaluation was considered absolutely necessary to define, for each investigated environment, the initial scenario under the specific air ventilation and human occupancy conditions established in a discretionary manner by each educational building (in any case coherent with the basic precautionary measures and recommendations provided by the Italian Government and applicable during the monitoring period). During the first evaluation stage, in order to collect all the necessary details on routine practices, the teachers were invited to fill a questionnaire reporting day by day the frequency and timing of doors and windows opening as well as the number of students present in the classroom (for most of the classrooms the number of students/pupils was constant over the monitoring period, only in few cases slight variations around the fixed number were reported, see schools 1, 2 and 9 in Table 1). After the preliminary evaluation allowing critical issues of the individual classrooms come to light, a detailed operating protocol to be implemented for the second-stage evaluation process was provided to teachers and school administrators. The operating protocol comprised the following list of recommendations addressed to promote air ventilation: a) to leave the classroom door always open during the occupancy hours; b) to open the windows for 10 min during the breaks between two consecutive teaching hours (for primary and secondary classrooms) or at time change (for kindergartens); c) when the actions above were not successful, to open the windows whenever the CO_2 concentration inside the classroom exceeded and/or was approaching 700 ppm, for the period of time necessary to adequately lower CO_2 values benefiting of the sensor mobile application providing real-time data. The provided recommendations are in line with the ventilation strategies inside indoor environments promoted by building environments-related international organizations such as REHVA (Federation of European Heating, Ventilation and Air Conditioning Associations) and ASHRAE (American Society of Heating, Ventilating and Air Conditioning Engineers) to primarily improve air quality (ASHRAE, 2020; REHVA, 2020). The achievement of adequate ventilation indoors through the implementation of similar recommendations has been also recognized in the recent scientific literature as the necessary condition to reduce airborne viral transmission (Morawska, 2021; Villanueva, 2021).

Table 1
Description of classrooms characteristics.

School	Classroom (level)	Floor surface (m^2)	Volume (m^3)	No. of windows	No. of students	Air ventilation	Daytime occupancy
1	1a: pre-school	35	112	1	10–11	natural	8 a.m. - 1 p.m.
	1b: primary	35	112	1 + 1 (lift-up)	5–6	natural	full time: 8 a.m. - 4 p.m.
2	pre-school	49	146	7 (lift-up)	12–15	natural	8 a.m. - 1 p.m.
3	3a: primary	46	147	4	13	natural	8:30 a.m. - 1:30 p.m.
	3b: primary	35	114	5	14	natural	
4	primary	50	152	2	20	natural	8 a.m. - 1:30 p.m.
5	secondary	43	128	2	11	natural	full time: 8:20 a.m. - 4:40 p.m.
6	secondary	42	136	2	20	natural	8:20 a.m. - 1:30 p.m.
7	secondary	45	155	1	12	natural	8:30 a.m. - 1:30 p.m.
8	primary	49	142	3	9	natural	8:30 a.m. - 12:40 p.m.
9	secondary	42	130	4	18–21	natural	8 a.m. - 1 p.m.

3.1. Real-time monitoring of CO_2 concentration and other environmental parameters

High temporal resolution monitoring of CO_2 concentration (ppm), temperature (°C) and relative humidity (%) was performed inside the selected classrooms through the deployment of several units of an integrated indoor air quality monitoring system (Nose, Befreest srl, Italy; one unit placed at each investigated location), shown in Fig. 1. The air quality monitoring system is available on the market in two versions: a) the basic version (NoseC) specific for CO_2 concentration monitoring; b) the advanced version (NoseP), properly set up for the simultaneous real-time monitoring of Total Volatile Organic Compounds (TVOCs), particulate matter (PM10, PM2.5) and CO_2 concentration. Both versions allow other micro-environmental parameters e.g., temperature and relative humidity to be monitored. With specific regard to the research purposes, the Nose version used in the present study is the basic one. The NoseC system is equipped with a nondispersive infrared (NDIR) sensor comprising an infrared source lamp, a light tube, a light filter and an infrared detector to measure CO_2 within the 0–40000 ppm range with an accuracy of ±30 ppm. The readings of all the monitored parameters were recorded with 2-min time resolution. The acquired data were collected and stored on a cloud platform through IoT technology and were easily accessible for the end user both for direct data visualization and download. The selection of the monitoring location inside the selected classrooms was properly made according to the representativeness criteria. The monitoring systems were placed at approximately 1.5 m from the floor and, when possible, in the center of the classrooms to make the readings as much as possible representative of the whole room volume. A distance of at least 1 m between the windows and the NoseC was guaranteed in each classroom to avoid air turbulence nearby the monitoring system resulting in potential fluctuations in data readings. For the same reason, both students and children (in the pre-school classrooms) were not allowed to get close to the instrumentation to avoid that the measurements could be affected by the direct exposure to exhaled CO_2. The monitoring activity was not contextually performed outdoors, therefore the outdoor CO_2 concentration was assumed to be constant and equal to 400 ppm (e.g., the global background value).

3.2. Inter-comparison activity

P Prior to the deployment at the educational buildings, eleven NoseC units were inter-compared inside one office at the Department of Biology of University of Bari. The inter-comparison activity was performed over 24 h (between 11th and January 12, 2021) in the meanwhile routine activities inside the office occurred. Details of the activities inside the university office i.e., opening and closing the windows, opening and closing the door, occupancy of the room by one or two persons, in terms of timing and duration, were annotated by the researchers on a file sheet to support the comprehension of the temporal trends of CO_2 concentration. The intercomparison activity was also based on the comparison of CO_2 measurements provided by NoseC sensors with real-time readings registered by AQ Guard monitoring instrument manufactured by Palas (Palas GmbH, Germany). It represents one of the most advanced and reliable analyzers currently available on the market, for the continuous monitoring of particulate matter, VOCs and CO_2 concentration in both indoor and outdoor settings. CO_2 concentration measurements made by AQ Guard analyzer are based on NDIR technology within the dynamic concentration range 0–5000 ppm. Although the AQGuard analyzer integrates top-quality and robust sensor technologies, it is not recognized as a scientific-grade reference instrument. Therefore its involvement in the inter-comparison activity is not intended for calibration purposes but in the view of a qualitative and quantitative comparison with the experimental data collected by the NoseC sensors employed in the present study.

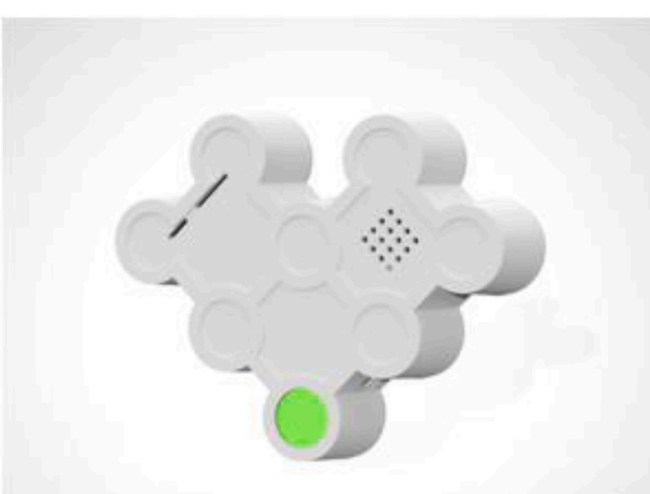

Fig. 1. NoseC monitoring system.

4. Results and discussion

4.1. Intercomparison results

The outcomes of the 24 h-intercomparison activity involving all the eleven NoseC systems and AQ Guard analyzer are shown in the Supplementary Material (Fig. 1S and Tables 1–2 S). The comparison of temporal variations of CO_2 concentrations (expressed in ppm) for all the employed devices is reported in Fig. 1S while the correlation coefficients and the percentage relative standard deviations are reported in Tables 1S and 2S, respectively. A good agreement has been overall observed for all the NoseC monitoring systems. The consistency of the collected data is visible by the overlapping of the temporal profiles (Fig. 1S) and is supported by the obtained values of the correlation coefficients ranging from 0.98 to 0.99 (Table 1S). At this regard, the percentage relative standard deviation determined for each single sensor revealed to be below 7% (Table 2S). When compared to the AQ Guard analyzer, the eleven NoseC sensors generally have overestimated the CO_2 concentrations over the explored concentration range (400–900 ppm). However, the percentage relative standard deviation determined for each NoseC sensor with respect to the AQ Guard analyzer is not significant reaching in only one case the maximum value of 14% (Table 2S). Based on the obtained intercomparison results and prior to the deployment of the NoseC monitoring systems inside the investigated classrooms, an offset procedure has been performed adjusting CO_2 concentrations measured by each individual sensor with respect to the corresponding overall mean value.

4.2. Discussion on CO_2 concentration data in the monitored classrooms

4.2.1. First-stage evaluation outcomes: preliminary considerations

The data collected during the first monitoring days in the investigated classrooms showed CO_2 mean concentrations during the school hours ranging from 720.7 to 1325 ppm with maximum values ranging from 867 e 3947 ppm (Table 2). The classrooms 3A (1381 ppm) and 6 (1325 ppm) showed the highest values of CO_2 mean concentrations while classrooms 2 (720.7 ppm) the lowest one. The limit value of 1000 ppm for indoor CO_2 concentration has been worldwide accepted according to the recommendations of the WHO (WHO Regional, 2000) and the American Society of Heating, Refrigeration, and Air conditioning Engineers (ASHRAE Standard 62) based on the outcomes of several observational and epidemiological studies (Branco et al., 2020). In this context, a study conducted by Simoni et al. (2010) enrolling schoolchildren (654 children of 46 classrooms) exposed to indoor CO_2 concentrations higher than 1000 ppm highlighted the outbreak of higher risk for dry cough and rhinitis. Moreover, CO_2 levels higher than 1000

ppm were associated with decreasing of cognitive scores (productivity and learning ability) (Allen et al., 2016) and with increasing of a) cardiovascular and respiratory symptoms, b) eyes and skin irritation, c) headache outbreak (Carreiro-Martins et al., 2016; MacNaughton et al., 2016). More recently, national recommendations in Spain suggested that indoor CO_2 concentrations should not exceed 700 ppm in classrooms and 550 ppm in hallways (Marr et al., 2020) in order to limit the COVID-19 transmission in schools. Notwithstanding recommended values at national and international level to improve indoor air quality and face the pandemic emergency, in this study the average concentrations of CO_2 measured in more than half of investigated classrooms (6 on 11 classrooms, 54%) exceeded the WHO recommended limit (1000 ppm) and for all classrooms CO_2 levels exceeded 700 ppm, suggested by Marr et al.,(2020) (Table 2). Moreover, with specific regard to classroom 5 and 6, it has been observed that CO_2 concentration reached maximum values equal to 2561 and 3947 ppm, respectively, suggesting a very high air stuffiness setting in the classrooms during school hours. Although the observed critical concentrations, during the first stage of evaluation the mean levels of CO_2 measured in the most of the investigated classrooms were lower than those reported for the classrooms enrolled in the framework of the European project SINPHONIE (Baloch et al., 2020) with only few exceptions (1325 and 1381 ppm for classroom 6 and 3, respectively). Similarly, the CO_2 mean levels observed in this study revealed to be lower than those documented for the European educational buildings in the cross-sectional European Union-funded HESE (Health Effects of School Environment) study and, more specifically, up to half of the mean values determined in 16 classrooms of 8 schools in Italy (Simoni et al., 2006, 2010); even if similar maximum values were found. On the other hand, according to Villanueva et al. (2021), the pre-school (classroom 2) was the educational environment showing the lowest mean and maximum values of CO_2 concentration probably due to the presence of seven transom windows always open (as reported in the questionnaires).

Fig. 2 shows daily variations of CO_2 concentration throughout the first monitoring day for the classrooms that exhibited the highest maximum values (Classroom 6: 2561 ppm and Classroom 5: 3947 ppm). Although the highest CO_2 level was registered for the secondary classroom 5, the classroom 6 showed CO_2 levels higher than 2000 ppm and 1000 ppm for longer periods of time, 40% and 75% of the school hours, respectively. On the other hand, CO_2 levels measured in classroom 5 were lower than 1000 ppm during 3 h out of 8,5 h (35% of the school time). It's important to underline that during the first day, inside the classroom 6, 20 students and 1 teacher were present while inside the classroom 5, the total number of bystanders was 12 (11 students and 1 teacher). Anyway, other classrooms characterized by a high number of persons, for instance the classroom 4 (21) and 9 (19), showed CO_2 levels lower than those monitored in classroom 6 probably due to a more efficient ventilation strategy in terms of frequency and duration of windows and door opening as well as to hourly cross-ventilation (Villanueva et al., 2021) (Fig. 2 and Table 2). This evidence supports the hypothesis that the number of persons is not the only factor that explains the CO_2 level behaviour.

Table 2
Mean, minimum and maximum values of CO2 concentration (ppm) calculated for the first monitoring days (FDs) when the developed operating protocol was not implemented,yet.

Classroom	Background CO_2 level (ppm)	Mean CO_2 level (ppm)	Max CO_2 level (ppm)
1A	358.9	1117	1712
1B	359.9	893.3	1166
2	333.9	720.7	867
3A	408.4	1381	1771
3B	412.1	882.8	1885
4	406.5	1010	1551
5	467.2	1097	3947
6	309.7	1325	2561
7	360.9	976.4	1482
8	402.3	895.5	1337
9	437.2	1032	1722

4.3. Second stage evaluation outcomes: effectiveness of the implementation of air ventilation protocol

After the first monitoring days, the proposed and standardized protocol (described in detail in sub-section 2.2) was applied in all the investigated classrooms. As a result, better scenarios were depicted for most of the classrooms as its possible to observe in Fig. 3, where the boxplot of CO_2 levels associated with the first stage evaluation (First Days FDs) and second stage evaluation (other days ODs) are reported. More specifically, ten out of eleven classrooms (91%) showed CO_2 mean levels lower than 1000 ppm and 4 classrooms (36%) lower than 700 ppm with maximum values lower than 1000 ppm. Only classroom 8 showed CO_2 levels worse than those detected in the first monitored days due to an ineffective implementation of the proposed protocol by non-compliant teachers and school administrators as deductible by the daily questionnaires not provided.

With the purpose of deepening the discussion on the outcomes of operating protocol implementation, the temporal profiles of CO_2 concentration measured during the first monitoring days and subsequently to the application of the following corrective measures: a) ventilation strategies and real-time data visualization, were compared. Limit and recommended values of 1000 and 700 ppm are also visualized for comparison. Fig. 4a shows, for example, the temporal variation of CO_2 concentration registered in the classroom 3A during the school hours in two different days: the first monitoring day when teachers discretionary decided when and for how long time both door and windows were opened and another day when tailored actions for air ventilation were taken according to the provided protocol. Even if hourly cross-ventilation between windows and door was promoted inside classroom 3A during the first days for example on 18th January (as reported in the dedicated questionnaires), CO_2 concentrations (mean value:1381 ppm, maximum value: 1771 ppm) were higher than those registered in the following days as occurred, for instance, on 20th January (mean value: 547 ppm; maximum value: 730 ppm). A further improvement was detected when (for example on 21st January, mean value: 463 ppm; maximum value: 635 ppm), in addition to the application of a proper air ventilation strategy, the temporal variation of CO_2 concentration has been frequently observed during the school hours allowing the teachers to promptly modulate the actions contextually with an increase in CO_2 concentration (Fig. 4b).

These findings obtained for classroom 3A were common to almost all classrooms and suggested that only looking at the real time data, it is possible to promote effective air exchanges able to lower CO_2 levels to background values. In fact, for example in Fig. 5 are shown the evolutions of CO_2 levels along school hours in the same classroom and during two days: when the teacher looks (21st January) and not looks (19th January) at real time CO_2 data. It is remarkable to underline that a tailored modulation of actions for air ventilation allowed for classroom 3A to maintain the CO_2 concentration at low levels preserving at the same time the thermal comfort of the students despite the cold temperatures registered during the monitoring period. Indeed, the mean indoor temperature registered during the first day (15.8 °C) was lower than that in the other days (T: 18.3 °C) when cross-ventilation conditions combined with data visualization were ensured. This finding, in substance, suggests the need for real time visualization of CO_2 levels to successful manage the air exchanges inside classrooms and promptly act in warning situations rather than using systematic ventilaton protocols at priori scheduled.

Similarly to classroom 3A, classroom 5 representing the worst case during the first-stage evaluation (CO_2 maximum value equal to 3947 ppm), after the application of the protocol was characterized by an overall improvement of the critical situation through the decreasing in

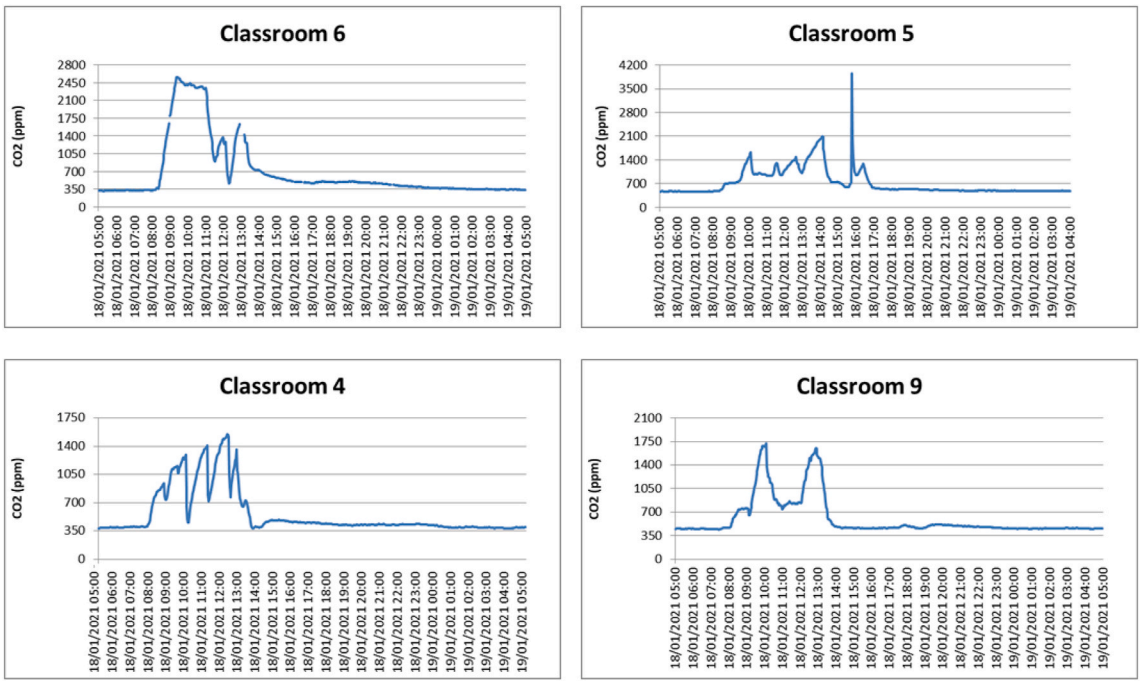

Fig. 2. Evolution of CO_2 levels in the classroom 6, 5, 4 and 9 during the one of first monitoring days.

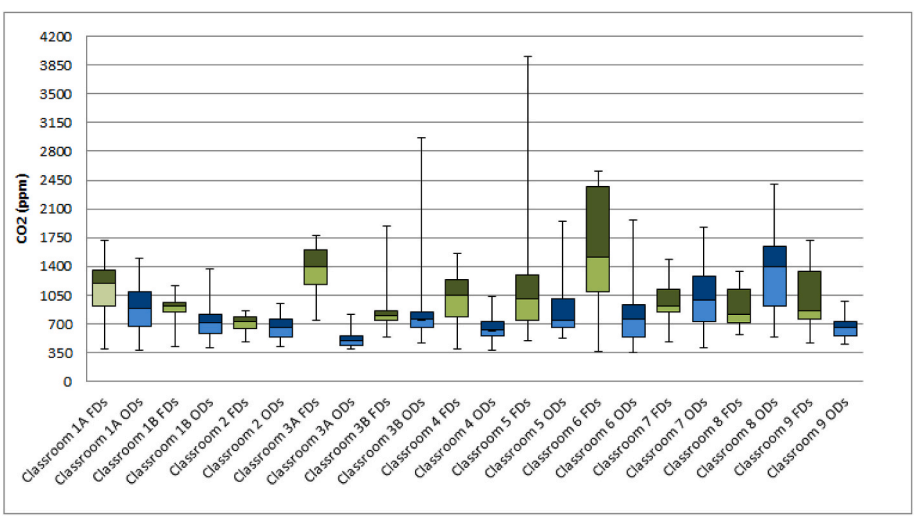

Fig. 3. Boxplot of CO_2 concentrations for all investigated classrooms associated with the first stage evaluation (FDs, green color) and second stage evaluation (other days ODs, blue color).

CO_2 levels. Nevertheless, the CO_2 concentrations constantly remained above the 700 ppm reaching peak values in some cases higher than 1000 ppm (as a mere example 26th January is reported in Fig. 6). This evidence can be explained by the absence of windows in the hallway facing the classroom that limited the effectiveness of the cross-ventilation. This is the case when structural limits of the educational building play a crucial role negatively affecting the indoor air quality and potentially promoting the airborne viral transmission (Villanueva et al., 2021).

4.4. Risk classification scheme

Most of the theoretical models that have been developed over the past decades for the simulation of airborne transmission of pathogens inside enclosed environments take origin from the model of aerosol infection by Wells and Riley, relating the amount of virus infection quanta inhaled by a susceptible person with the probability of the same to be infected (Riley et al., 1978; Gammaitoni and Nucci, 1997). The development and application of Wells-Riley based models has allowed scientists over the years to estimate the infection risk for specific diseases (for instance rhinovirus, SARS) and under several indoor settings i.e., hospitals, cars, airplanes (Wagner et al., 2009; Knibbs et al., 2011). More recently, based on the insights coming from the modelling studies of Miller et al., (2021), Buonanno at al., (2020a, 2020b) and Beggs (2020), Peng and Jimenez developed a version of the theoretical model making it tailored to estimate COVID-19 infection risk only due to room-level aerosol transmission (droplets or contact/fomites transmission were not included assuming that the social distancing is respected) (Jimenez, J.L., 2020). Within the proposed model by Peng and Jimenez, CO_2 concentration has been used as a proxy of SARS-CoV-2 concentration indoors under specific assumptions and conditions (e.g., the presence of at least one infected person in the considered

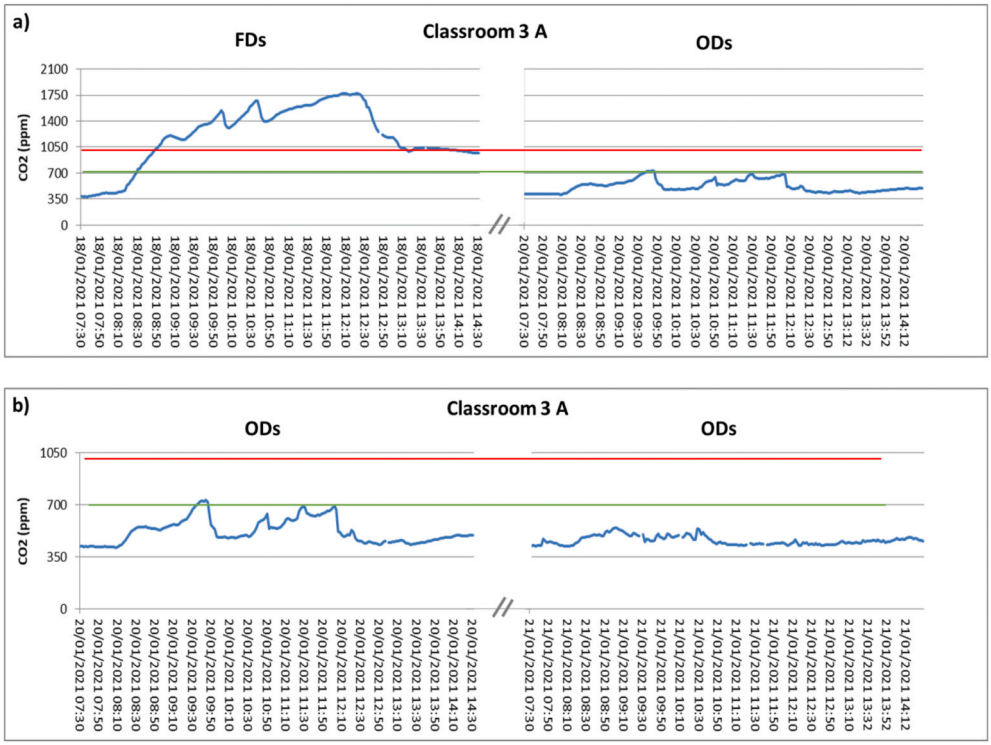

Fig. 4. Evolution of CO_2 levels in the classroom 3A during one of first monitoring days (FDs) and during one of the following days (ODs) when a proper protocol of ventilation was implemented (a) and when the temporal variation of CO_2 concentration has been frequently observed during the school hours thanks to real-time visualization of data (b).

environment). Analytical expressions of CO_2-based risk proxies were then accordingly derived by Peng and Jimenez and applied to various typical indoor settings, including classrooms. Therefore, on the basis of the outcomes of the monitoring campaign (CO_2 values before and after the application of the operating protocol) as well as the probability of infection estimated under the assumptions of the model by Peng and Jimenez and for selected classroom scenarios, a 4 level-risk classification scheme (from low risk to very high risk) has been drawn up in the context of the present study, as shown in Table 3. Four risk levels have been identified based on the risk estimates related to both CO_2 peak concentrations during the school hours and/or school-time average CO_2 concentrations. All the actions that can be applied to ensure an adequate air ventilation inside classrooms are reported in the classification scheme, including operating actions based on the variation of timing and frequency of door and windows opening, classroom setting changes (number of students allowed to be present) as well as building-related changes like the implementation of mechanical systems for air ventilation and purification. The above mentioned actions are also reported in each risk class as elements of a flow-chart (see second row of the table) intended to be followed to guide step by step the end user (school administrators and teachers) in the advancement of the investigated classroom from higher risk level class to a lower one. In detail, the CO_2 concentration thresholds are proposed by us on the basis of the risk probability (representing the risk for one susceptible subject to re-inhale the air exhaled by other bystanders) estimated through the simulations of the estimator developed by Peng and Jimenez (2020) considering the different expositive scenarios (number of students, classroom dimensions and characteristics, ventilation conditions) encoutered during survelliance activity of the present study. Therefore, the risk classes are associated with CO_2 concentration both intended as peak and averaged values: low risk class for CO_2 concentration up to 700 ppm, moderate risk class for CO_2 concentration ranging from 700 to 800, high risk class for CO_2 concentration ranging from 800 to 1000 ppm and very high risk class for CO_2 levels above the 1000 ppm (the proposed values include background value equal to 400 ppm). Following the application of the operating protocol for air ventilation and of the proposed risk classification scheme (based on the CO_2 school-time averaged concentration), here are reported the outcomes: 4 classrooms have been classified as low-risk environments where no additional actions were acquired (classrooms n.3A, n. 2, n. 4 and n. 9); 4 classroms as moderate-risk environments (classrooms n. 1B, n. 3B, n. 5 and n. 6); 2 classrooms as high-risk environments (classrooms n. 1A and n. 7) and finally 1 classroom as very high-risk environment (classroom n. 8), affected by building structural limits and where mechanical ventilation systems are needed. It is remarkable to underline that the proper implementation of the air ventilation protocol (second-stage evaluation) allowed classroom 3A to step forward from very high-risk class to low risk class avoiding in this manner a potential SARS-CoV-2 outbreak inside the where the presence of an infected student was registered. This evidence highlights the potentialities of the proposed approach.

5. Conclusions

Although suitable measures to prevent SARS-CoV-2 transmission were recommended in all European countries in accordance with the WHO, educational buildings often fail in contagion containment due to the presence of a high number of students inside enclosed environments for several hours a day. In these conditions, indeed, the probability that a subject re-inhales the air exhaled by another potentially infected bystander and thus, the SARS-CoV-2 transmission probability result relatively high. Therefore, in order to safely promote the school reopening, adequate ventilation plans able to guarantee more effective fresh air exchanges should be adopted. In this pilot study, a surveillance activity based on real time monitoring of CO_2 levels, was conducted inside 9 schools (11 classrooms) located in Apulia Region (South of Italy) in order to evaluate the effectiveness of their ventilation protocols and suggest tailored corrective actions able to limit SARS-CoV-2 transmission risk. The development of tailored operating protocols of air

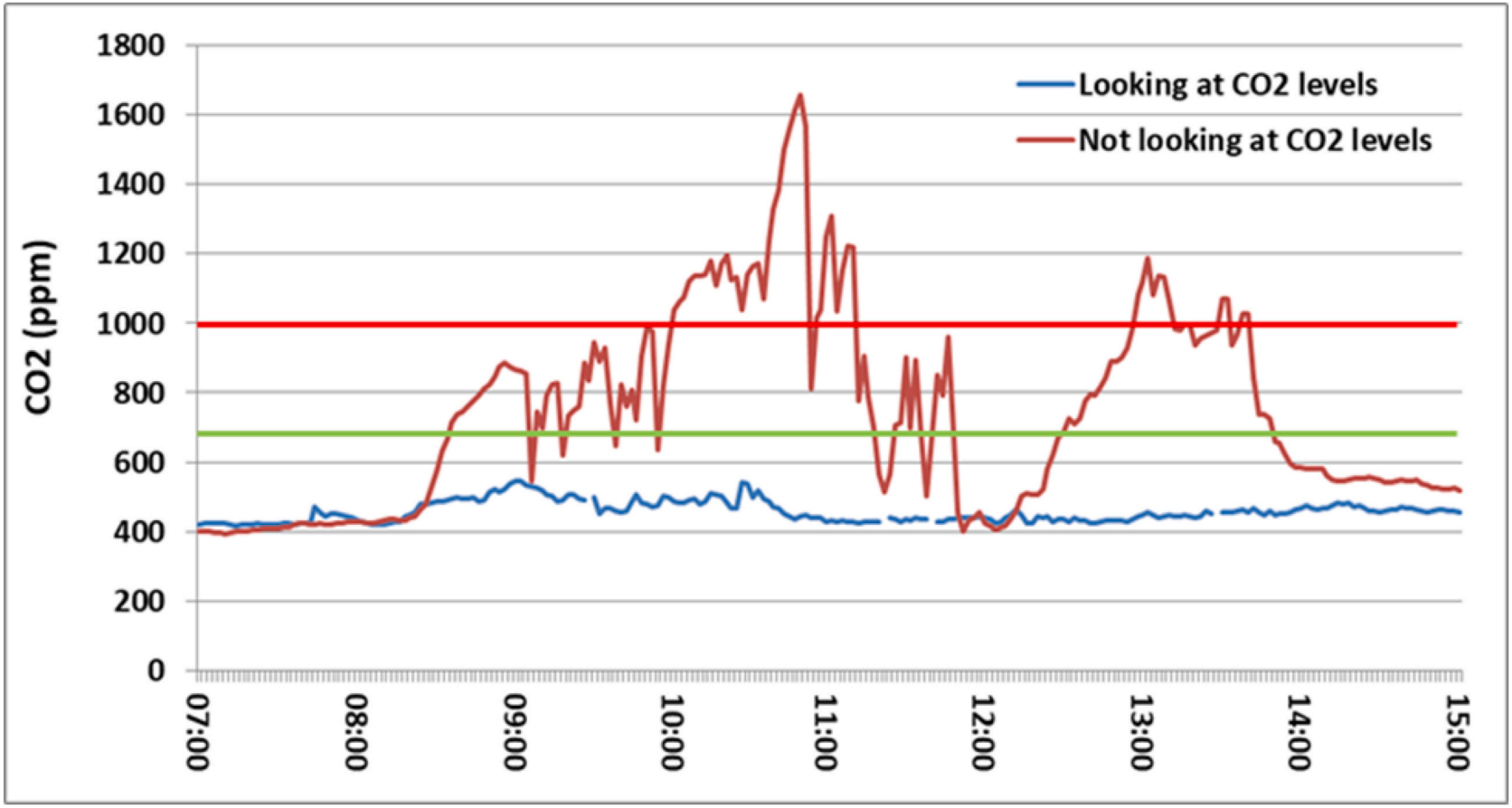

Fig. 5. Evolution of CO_2 levels in the classroom 3A in two different days when teacher looks and not looks at real time CO_2 levels.

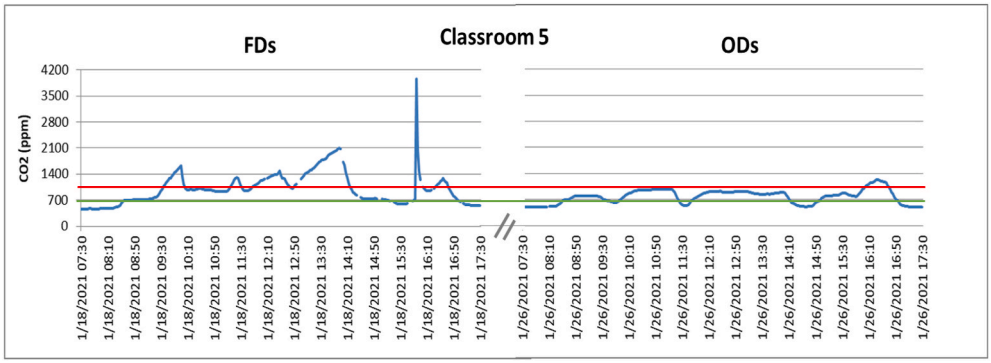

Fig. 6. Evolution of CO_2 levels in the classroom 5 during one of first monitoring days (FDs) and during one of the following days (ODs) when a proper protocol of ventilation was implemented.

Table 3
Risk classification scheme.

Risk Class	LOW RISK	MODERATE RISK	HIGH RISK	VERY HIGH RISK
*Actions**	No actions nedeed	Apply action A If A active, apply B If A & B both active, apply C If A, C active apply D	Apply A & B If A & B both active, apply C If A, C active apply D If A, C, D active apply E	Apply A & C If A, C active apply D If A, C, D active apply E
CO_2 peak concentration and/or school time-averaged concentration	< 700 ppm	> 700 ppm < 800 ppm	> 800 ppm < 1000 ppm	> 1000 ppm

* A: door always open; B: windows open for 10 min at midday; C: windows open for 10 min at the end of teaching hour and/or at hour change; D: setting change (e.g., windows opening time, number of pupils/students..); E: infrastructure changes needed.

ventilation and their prompt implementation in relation to the real time visualization of CO_2 levels, allowed to promote more effective air exchanges while guaranteeing the thermal comfort of students. Anyway, even if real-time monitoring of CO_2 levels and the implementation of proper protocols were provided, for some classrooms the only natural ventilation resulted to be not effective to guarantee adequate air exchanges due to building structural limits. Therefore, in these cases, further strategies based on the installation of heating, ventilation and air conditioning systems and air cleaner devices are needed to ensure adequate indoor ventilation and guarantee a safe school life during the pandemic.

Declaration of competing interest

The authors declare no conflict of interest.

Acknowledgements:

Special acknowledgements are for LabService Analytica srl (Dr. Antonio Fornaro) for the precious technical support.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2021.111560.

Credit roles

Alessia Di Gilio, Conceptualization and methodology, sampling and analysis, Data curation, statistical elaboration, writing, Writing – review & editing, Supervision, Jolanda Palmisani, Conceptualization and methodology, sampling and analysis, Data curation, Writing – review & editing, Supervision, Manuela Pulimeno, Funding acquisition, Fabio Cerino, Funding acquisition, Mirko Cacace, Funding acquisition, Alessandro Miani, Funding acquisition, Gianluigi de Gennaro, Conceptualization and methodology, Supervision, Funding acquisition.

References

Afshari, A., Ekberg, L., Forejt, L., Mo, J., Rahimi, S., Siegel, J., Chen, W., Wargocki, P., Zurami, S., Zhang, J., 2020. Electrostatic precipitators as an indoor air cleaner – a literature review. Sustainability 12 (21), 8774. https://doi.org/10.3390/su1221877.

Allen, J.G., MacNaughton, P., Satish, U., Santanam, S., Vallarino, J., Spengler, J.D., 2016. Associations of cognitive function scores with carbon dioxide, ventilation and volatile organic compounds exposures in office workers: a controlled exposure study of green and conventional office environments. Environ. Health Perspect. 124, 805–812. https://doi.org/10.1289/ehp.1510037.

Allen, J., Jones, E., Dedesko, S., Cedeno-Laurent, J., Young, A., 2020. 5-Step Guide to Checking Ventilation Rates in Classrooms, Healthy Buildings for Health. Harvard T. H. Chan. https://schools.forhealth.org/ventilation-guide/.

Annesi-Maesano, I., Hulin, M., Lavaud, F., Raherison, C., Kopferschmitt, C., De Blay, F., Charpin, D.A., Denis, C., 2012. Poor air quality in classrooms related to asthma and rhinitis in primary schoolchildren of the French 6 Cities Study. Thorax 67, 682–688. https://doi.org/10.1136/thoraxjnl-2011-200391.

ASHRAE, 2020. American Society of Heating Refrigerating, and Air Conditioning Engineers (ASHRAE), 2020. COVID-19 (CORONAVIRUS) Preparedness Resources.

Baloch, M.R., Maesano, C.N., Christoffersen, J., Banerjee, S., Gabriel, M., Csobod, E., de Oliveira, F.E., Annesi-Maesano, I., 2020. Indoor air pollution, physical and comfort

parameters related to schoolchildren's health. Data from the European SINPHONIE study. Sci. Total Environ. 739, 139870. https://doi.org/10.1016/j.scitotenv.2020.139870 on behalf of the SINPHONIE study.

Barbieri, P., Zupin, L., Licen, S., Torboli, V., Semeraro, S., Cozzutto, S., Palmisani, J., Di Gilio, A., de Gennaro, G., Fontana, F., Omiciuolo, C., Pallavicini, A., Ruscio, M., Crovella, S., 2021. Molecular detection of SARS-CoV-2 from indoor air samples in environmental monitoring needs adequate temporal coverage and infectivity assessment. Environ. Res. 111200 http://doi.or/10.1016/j.envres.2021.111200.

Beggs, C.B., 2020. Is there an airborne component to the transmission of COVID-19?: a quantitative analysis study. MedRXiv. https://doi.org/10.1101/2020.05.22.20109991.

Beggs, C., Noakes, C., Sleigh, P., Fletcher, L., Siddiqi, K., 2003. The transmission of tuberculosis in confined spaces: an analytical review of alternative epidemiological models. The International Journal[g1] of Tuberculosis and Lung Disease 7, 1015–1026.

Branco, B.P.T.B.S., Alvim-Ferraz, M.C.M., Martins, F.G., Ferraz, C., Vaz, L.G., Sousa, S.I. V., 2020. Impact of indoor air pollution in nursery and primary schools on childhood asthma. Sci. Total Environ. 745, 140982. https://doi.org/10.1016/j.scitotenv.2020.140982.

Buonanno, G., Morawska, L., Stabile, L., 2020a. Quantitative assessment of the risk of airborne transmission of SARS-CoV-2 infection: prospective and retrospective applications. Environ. Int. 145, 106112.

Buonanno, G., Stabile, L., Morawska, L., 2020b. Estimation of airborne viral emission: quanta emission rate of SARS-CoV-2 for infection risk assessment. Environ. Int. 141, 105794. https://doi.org/10.1016/j.envint.2020.105794.

Carreiro-Martins, P., Papoila, A.L., Caires, I., Azevedo, S., Cano, M.M., Virella, D., Leiria-Pinto, P., Teixeira, J.P., Rosado-Pinto, J., Annesi-Maesano, I., Neuparth, N., 2016. Effect of indoor air quality of day care centers in children with different predisposition for asthma. Pediatr. Allergy Immunol. 27, 299–306. https://doi.org/10.1111/pai.12521.

Cheek, E., Guercio, V., Shrubsole, C., Dimitroulopoulou, S., 2021. Portable air purification: review of impacts on indoor air quality and health. Sci. Total Environ. 766, 142585.

Curtius, J., Granzin, M., Schrod, J., 2021. Testing mobile air purifiers in a school classroom: reducing the airborne transmission risk for SARS-CoV-2. Aerosol Sci. Technol. https://doi.org/10.1080/02786826.2021.1877257.

de Gennaro, G., Farella, G., Marzocca, A., Mazzone, A., Tutino, M., 2013. Indoor and outdoor monitoring of volatile organic compounds in school buildings: indicators based on health risk assessment to single out critical issues. Int. J. Environ. Res. Publ. Health 10 (12), 6273–6291.

de Gennaro, G., Dambruoso, P., Demarinis Loiotile, A., Di Gilio, A., Giungato, P., Tutino, M., Marzocca, A., Mazzone, A., Palmisani, J., Porcelli, F., 2014. Indoor air quality in schools. Environ. Chem. Lett. 12 (4), 467–482.

de Gennaro, G., De Marinis Loiotile, A., Fracchiolla, R., Palmisani, J., Saracino, M.R., Tutino, M., 2015. Temporal variation of VOC emission from solvent and wood water based wood stains. Atmos. Environ. 115, 53–61. https://doi.org/10.1016/j.atmosenv.2015.04.021.

de Oliveira, P.M., Mesquita, L.C.C., Gkantonas, S., Giusti, A., Mastorakos, E., 2021. Evolution of spray and aerosol from respiratory releases: theoretical estimates for insight on viral transmission. Proceedings of the Royal Society A 477, 20200584. https://doi.org/10.1098/rspa.2020.0584.

Di Gilio, A., Farella, G., Marzocca, A., Tutino, M., de Gennaro, G., 2017. Indoor/outdoor air quality assessment at school near the steel plant in Taranto (Italy). Advances in Meteorology 1526209.

Drossinos, Y., Stilianakis, N., 2020. What aerosol physics tells us about airborne pathogen transmission. Aerosol. Sci. Technol. 54 (6), 639–643. https://doi.org/10.1080/02786826.2020.1751055.

EPA's Guide to Air Cleaners in the Home https://www.epa.gov/sites/production/files/2018- 07/documents/guide_to_air_cleaners_in_the_home_2nd_edition.pdf.

Federation of European Heating. Ventilation and Air Conditioning Associations (REHVA), 2020. Covid-19 Guidance Document. https://www.rehva.eu/fileadmin/user_upload/REHVA_COVID-19_guidance_document_V3_03082020.pdf.

Gammaitoni, L., Nucci, M.C., 1997. Using a mathematical model to evaluate the efficacy of TB control measures. Emerg. Infect. Dis. 335–342.

Gralton, J.E., Tovey, M.L., McLaws, W., Rawlinson, D., 2011. The role of particle size in aerosolised pathogen transmission: a review. J. Infect. 62 (1), 1–13. https://doi.org/10.1016/j.jinf.2010.11.010.

Jayaweera, M., Perera, H., Gunawardana, B., Manatunge, J., 2020. Transmission of COVID-19 virus by droplets and aerosols: a critical review on the unresolved dichotomy. Environ. Res. 188, 109819.

Jimenez, J.L.. COVID-19 Aerosol Transmission Estimator. https://tinyurl.com/covid-estimator. (Accessed 1 July 2020).

Knibbs, L.D., Morawska, L., Bell, S.C., Grzybowski, P., 2011. Room ventilation and the risk of airborne infection transmission in 3 health care settings within a large teaching hospital. Am. J. Infect. Contr. 39 (10), 866–872. https://doi.org/10.1016/j.ajic.2011.02.014.

Liao, C.M., Chang, C.F., Liang, H.M., 2005. A probabilistic transmission dynamic model to assess indoor airborne infection risks. Risk Anal. 25 (5), 1097–1107. https://doi.org/10.1111/j.1539-6924.2005.00663.x.

MacNaughton, P., Spengler, J.D., Vallarino, J., Santanam, S., Satish, U., Allen, J., 2016. Environmental perceptions and health before and after relocation to a green building. Build. Environ. 104, 138–144. https://doi.org/10.1016/j.buildenv.2016.05.011.

Marr, L., Miller, S., Prather, K., Haas, C., Bahnfleth, W., Corsi, R., Tang, J., Herrmann, H., Pollitt, K., Ballester, J., Jiménez, J.L., 2020. FAQs on Protecting Yourself from Aerosol Transmission. Version: 1.87 [WWW Document]. URL. accessed 04.03.21. http://tinyurl.com/faqs-aerosol.

Mikhailov, E., Vlasenko, S., Niessner, R., Poschl, U., 2004. Interaction of aerosol particles composed of protein and salts with water vapor: hygroscopic growth and microstructural rearrangement. Atmos. Chem. Phys. 4 (2), 323–350. https://doi.org/10.5194/acp-4-323-2004.

Miller, S.L., Nazaroff, W.W., Jimenez, J.L., Boerstra, A., Buonanno, G., Dancer, S.J., Kurnitski, J., Marr, L.C., Morawska, L., Noakes, C., 2021. Transmission of SARS-CoV-2 by inhalation of respiratory aerosol in the Skagit Valley Chorale superspreading event. Indoor Air 31, 314–323. https://doi.org/10.1111/ina.12751.

Minguillón, M.C., Querol, X., Riediker, M., Felisi, J.M., Garrido, T., Alastuey, A., Bekö, G., Nehr, S., Wiesen, P., Carslaw, N., 2020. Guide for Ventilation towards Healthy Classrooms. COST Action CA17136 Report. CSIC publications. http://hdl.handle.net/10261/225519.

Morawska, L., Tang, J.W., Bahnfleth, W., Bluyssen, P.M., Boerstra, A., Buonanno, G., Cao, J., Dancer, S., Floto, A., Franchimon, F., Haworth, C., Hogeling, J., Isaxon, C., Jimenez, J.L., Kurnitski, J., Li, Y., Loomans, M., Marks, G., Marr, L.C., Mazzarella, L., Melikov, A.K., Miller, S., Milton, D.K., Nazaroff, W., Nielsen, P.V., Noakes, C., Peccia, J., Querol, X., Sekhar, C., Seppänen, O., Tanabe, S.-I., Tellier, R., Tham, K.W., Wargocki, P., Wierzbicka, A., Yao, M., 2020. How can airborne transmission of COVID-19 indoors be minimised? Environ. Int. 142, 105832. https://doi.org/10.1016/j.envint.2020.105832.

Nicas, M., Nazaroff, W.W., Hubbard, A., 2005. Toward understanding the risk of secondary airborne infection: emission of respirable pathogens. J. occupational environmental hygiene 2, 143–154. https://doi.org/10.1080/15459620590918466.

Noakes, C., Beggs, C., Sleigh, P., Kerr, K., 2006. Modelling the transmission of airborne infections in enclosed spaces. Epidemiol. Infect. 134 (5), 1082–1091. https://doi.org/10.1017/S0950268806005875.

Peng, Z., Jimenez, J.L., 2020. Exhaled CO2 as COVID-19 infection risk proxy for different indoor environments and activities, 2021 Environ. Sci. Technol. Lett. 8 (5), 392–397. https://doi.org/10.1021/acs.estlett.1c00183.

Riediker, M., Monn, C., 2021. Simulation of SARS-CoV-2 aerosol emissions in the infected population and resulting airborne exposures in different indoor scenarios. Aerosol Air Qual. Res. 21, 200531. https://doi.org/10.4209/aaqr.2020.08.0531.

Riley, E.C., Murphy, G., Riley, R.L., 1978. Airborne spread of measles in a suburban elementary school. Am. J. Epidemiol. 107, 421–432. https://doi.org/10.1093/oxfordjournals.aje.a112560.

Rudnick, S., Milton, D., 2003. Risk of indoor airborne infection transmission estimated from carbon dioxide concentration. Indoor Air 13, 237–245. https://doi.org/10.1034/j.1600-0668.2003.00189.x.

Setti, L., Passarini, F., de Gennaro, G., Barbieri, P., Perrone, M.G., Borelli, M., Palmisani, J., Di Gilio, A., Piscitelli, P., Miani, A., 2020. Airborne transmission route of COVID-19: why 2 meters/6 feet of inter-personal distance could not Be enough. Int. J. Environ. Res. Publ. Health 17, 2932. https://doi.org/10.3390/ijerph17082932.

Simoni, M., Annesi-Maesano, I., Sigsgaard, T., Norback, D., Wieslander, G., Nystad, W., Canciani, M., Sestini, P., Viegi, G., 2010. School air quality related to dry cough, rhinitis and nasal patency in children. Eur. Respir. J. 35, 742–749. https://doi.org/10.1183/09031936.00016309.

Villanueva, F., Notario, A., Cabañas, B., Martín, P., Salgado, S., Gabrield, M.F., 2021. Assessment of CO2 and aerosol (PM2.5, PM10, UFP) concentrations during the reopening of schools in the COVID-19 pandemic: the case of a metropolitan area in Central-Southern Spain. Environ. Res. 197, 111092. https://doi.org/10.1016/j.envres.2021.111092.

Vuorinen, V.M., Aarnio, M., Alava, V., Alopaeus, N., Atanasova, M., Auvinen, N., Balasubramanian, H., Bordbar, P., Er€ast€o, R., Grande, et al., 2020. Modelling aerosol transport and virus exposure with numerical simulations in relation to SARS-CoV-2 transmission by inhalation indoors. Saf. Sci. 130, 104866. https://doi.org/10.1016/j.ssci.2020.104866.

WHO Regional, 2000. Air Quality Guidelines for Europe, second ed. https://www.euro.who.int/_data/assets/pdf_file/0005/74732/E71922.pdf.

Zhu, S., Jenkins, S., Addo, K., Heidarinejad, M., Romo, S.A., Layne, A., Ehizibolo, J., Dalgo, D., Mattise, N.W., Hong, F., Adenaiye, O.O., bueno de Mesquita, J.P., Albert, B.J., Washington-Lewis, R., german, J., Taj, S., Youssefi, S., Milton, D.K., Srebric, J., 2020. Ventilation and laboratory confirmed acute respiratory infection (ari) rates in college residence halls in college park, Maryland. Environ. Int. 137, 10553. https://doi.org/10.1016/j.envint.2020.105537.