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REVIEW

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# A multi-layered strategy for COVID-19 infection prophylaxis in schools: A review of the evidence for masks, distancing, and ventilation

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## Abstract

Implications for the academic and interpersonal development of children and adolescents underpin a global political consensus to maintain in-classroom teaching during the ongoing COVID-19 pandemic. In support of this aim, the WHO and UNICEF have called for schools around the globe to be made safer from the risk of COVID-19 transmission. Detailed guidance is needed on how this goal can be successfully implemented in a wide variety of educational settings in order to effectively mitigate impacts on the health of students, staff, their families, and society. This review provides a comprehensive synthesis of current scientific evidence and emerging standards in relation to the use of layered prevention strategies (involving masks, distancing, and ventilation), setting out the basis for their implementation in the school environment. In the presence of increasingly infectious SARS-Cov-2 variants, in-classroom teaching can only be safely maintained through a *layered strategy* combining multiple protective measures. The precise measures that are needed at any point in time depend upon a number of dynamic factors, including the specific threat-level posed by the circulating variant, the level of community infection, and the political acceptability of the resultant risk. By consistently implementing appropriate prophylaxis measures, evidence shows that the risk of infection from in-classroom teaching can be dramatically reduced. Current studies indicate that wearing high-quality masks and regular testing are amongst the most important measures in preventing infection transmission; whilst effective natural and mechanical ventilation systems have been shown to reduce infection risks in classrooms by over 80%.

**KEYWORDS**
air purification, infection prophylaxis in school classrooms, masking and physical distancing, mechanical ventilation, natural ventilation

## 1 | INTRODUCTION

According to the World Health Organization (WHO) "The [COVID-19] pandemic has caused the most catastrophic disruption to education in history."[1] As a result, educational and governmental authorities have become increasingly aware of the widespread nature of poor indoor environmental quality (IEQ) in classrooms, which epidemiologists, public health experts, and building services engineers have been sounding warnings over for decades.[2–4] Despite appeals by both the WHO and UNICEF for schools to be made safer, by adopting measures to minimize transmission of the SARS-CoV-2 virus, there has been little progress, by way of a coherent transnational directives, on how this should be achieved. Part of the reason that decisive action to reduce transmission in schools has been delayed may be because the factors influencing the nature of indoor transmission of SARS-CoV-2 were poorly understood initially, and the role of aerosol transmission was downplayed.[5] It was not until 30 April 2021, more than 12 months after first declaring COVID-19 a pandemic, that the WHO formally acknowledged that the virus was airborne.[6] Whilst more than 2 years into the pandemic, on 23 March 2022, the U.S. White House announced for the first time that "the most common way COVID-19 is transmitted from one person to another is through tiny airborne particles of the virus hanging in indoor air."[7]

Overwhelming evidence of continued widespread disruption to the education of hundreds of millions of students worldwide[8] coupled with the mental health, wellbeing, economic, and social impacts associated with lockdowns and school closures,[9,10] has underscored the importance of decisive action to reduce in-school transmission. Gurdasani et al.[11] argue that mass infection is not an option since it risks leaving an entire generation with chronic health problems and disabilities, compounded by long-term personal and economic impacts.

It was established, during the Delta outbreak (using cluster tracing and calibrated agent-based epidemiological models), that the control of SARS-CoV-2 spread in schools (as defined by $R < 1$) requires a combination of more than one preventive measure.[12,13] Understanding modes of transmission and their relative importance, in any given context, is therefore central to the implementation of effective public health interventions (Appendix S1).[14] In support of this aim, the paper presented here provides a synthesis of up-to-date scientific information on the role of (1) physical distancing, (2) masks, and (3) ventilation and air purification as critical elements in the creation of a multi-layered prophylaxis strategy for schools and educational buildings. The work is intended to update, synthesize, and supplement previously published findings and reviews.[15,16,17,18]

**Practical Implications**

- Natural, mechanical, and hybrid ventilation strategies, to reduce the risk of infection with SARS-CoV-2 in school classrooms, are evaluated in the context of international standards and emerging guidelines.
- The need to maintain masking protocols to address short- and long-range transmission risks indoors is explored, alongside evidence of the acceptability of masking in schools.
- Strategies to reduce the risks of cross-infection arising from respiratory jets and from directed air currents, resulting from ventilation and purification strategies, are discussed.
- Guidance on the use of $CO_2$ sensors as proxy indicators of indoor air quality in classrooms is provided, alongside the evidence for, and constraints to, further reducing threshold limiting values.
- Recommendations for additional air cleaning strategies are provided, with particular attention given to the strengths and limitations of using mobile air purifiers.

## 2 | SEARCH STRATEGY AND SELECTION CRITERIA

We searched the National Library of Medicine PubMed database on June 14, 2022, using the search terms "SARS-CoV-2", "COVID", "schools", and "ventilation" for articles published in English up to June 12, 2022. We included abstracts and reports from meetings only if they related directly to previously published work. We found 2035 articles related to the transmission of COVID-19 in a wide range of settings. We then filtered these results to include only those that focused on COVID-19 'prevention', which yielded 1606 results. We then included articles if they provided evidence to support the use of individual or multiple prophylaxis measures to prevent or reduce the transmission of COVID-19 in schools and similar educational contexts. In addition to the PubMed publications, we also included articles from the German Federal Environment Agency (Umweltbundesamt) on topics related to ventilation and COVID-19 prophylaxis in schools.

## 3 | PHYSICAL DISTANCING AND MASKS

A number of studies have attempted to define a safe physical distance from *direct* transmission on the basis of the furthest distance that droplets produced by coughing can reach. The results of such studies show that environmental parameters, in particular air speed and direction, can play a significant role in influencing the distance which respiratory droplets can travel.[19,20,21] Using a modified version of the Wells-Riley model, Sun and Zhai[22] determined that the minimum safe distance for regular social activities (e.g. breathing and talking) indoors was 1.6–3 m; however, they note that occupant density, ventilation rate and effectiveness, and exposure time have a marked influence on infection probability. Moreover, in the absence of masks, it has been shown that large droplets can be transported more than 2 m by coughing and over 6 m by sneezing, under typical room temperature and humidity conditions (20 °C; 50% RH).[23,24] Meta-analysis, involving over 200 observational and comparative studies, confirms that effective protection against *direct infections* is provided by physical distancing (of 1 m or more) and the consistent wearing of quality-assured face masks (at least surgical masks or medical grade mouth-nose protection [MNP])[25] along with consistent hand hygiene.

The risk of *indirect infection* is also significantly reduced by wearing masks, with FFP2/N95 (and FFP3/N99) grade masks being particularly effective against aerosol transmission.[26,27] Cross-sectional studies show that communities with high reported mask-wearing and physical distancing have the highest predicted probability of transmission control.[28] Other measures, such as ventilation or mobile air purifiers, do not obviate the need to wear masks during the pandemic; rather they serve to provide an additional layer of protection against *indirect* infections. Moreover, research shows that the efficacy of masks is non-linear and is highly dependent on the airborne viral concentration in the room air. Using direct measurements of SARS-CoV-2 in air samples and population-level infection probabilities, Cheng et al.[26] determined that the viral load in most environments is sufficiently low for masks to be effective in reducing airborne transmission. To achieve this benefit, masks must always be worn correctly, that is, completely covering the mouth and nose and fitting as tightly as possible (i.e. without air gaps at the perimeter).

Masks should be worn by everyone during classroom teaching, including, as far as possible, the teachers, because speaking frequently and loudly accounts for a particularly large proportion of the respiratory droplet and aerosol emissions in a room.[29,30] The consequences of an unmasked teacher reading in class whilst in an infectious state were clearly illustrated in the COVID-19 outbreak at an elementary school in Marin County, California (May 2021) where the attack rate in the front two rows (closest to the teachers desk) was 80% and in the back three rows 28%.[13] For practical reasons and to minimize any negative effects on the teaching activities, teachers could alternate between wearing surgical masks and FFP2/N95 masks, depending on the specific needs of an activity and the applicable regulations.

Despite media controversy and false reporting,[31] there is little data attesting to adverse effects from mask wearing in children, and when used appropriately, they are not expected.[32] Moreover, research suggests that children actually tolerate mask wearing better than their parents realize.[33] During school breaks, the students should be encouraged to spend time outdoors, where they can safely remove their masks. Masks should still be required in transit zones (hallways, stairwells etc.) as well as in washrooms and other confined indoor spaces. There is no evidence that mandatory masking has exerted a negative effect on social distancing between individuals when queuing or in crowded spaces; on the contrary, evidence shows that masks appear to serve as a signal to increase distancing.[34] Appropriate break times outdoors should be observed because the continuous wearing of surgical masks (and even more so tightly fitting FFP2/N95 masks) can be perceived as a physiological strain.

Extrapolating such findings to the outdoor setting is challenging, Rowe et al.[35] developed a simplified analytical model to compare the relative level of exposure occurring between comparable (in terms of occupant density) outdoor and indoor settings. Their findings confirm that the risk of *indirect* transmission outdoors is typically orders of magnitude lower than that of indoors; however, they note that situations of temperature inversion and low wind speeds (i.e. those which commonly exacerbate atmospheric pollution) could result in levels of outdoor transmission close to those indoors, especially in crowded spaces.[35] On the basis of these findings, it can be inferred that outside the school building (e.g. in the schoolyard), masks do not typically need to be worn provided sufficient distance is maintained (min. 1.5 m). Conversely, when in close proximity outdoors (i.e. <1.5 m), masks should also be worn, to avoid direct infections; for this purpose, simple mouth–nose coverings are sufficient.

Physical distancing should be maintained both indoors and outdoors to reduce the risks of direct transmission. The primary function served by the wearing of face masks (i.e. source control) cannot be replaced by distancing, ventilation, or air purification measures.

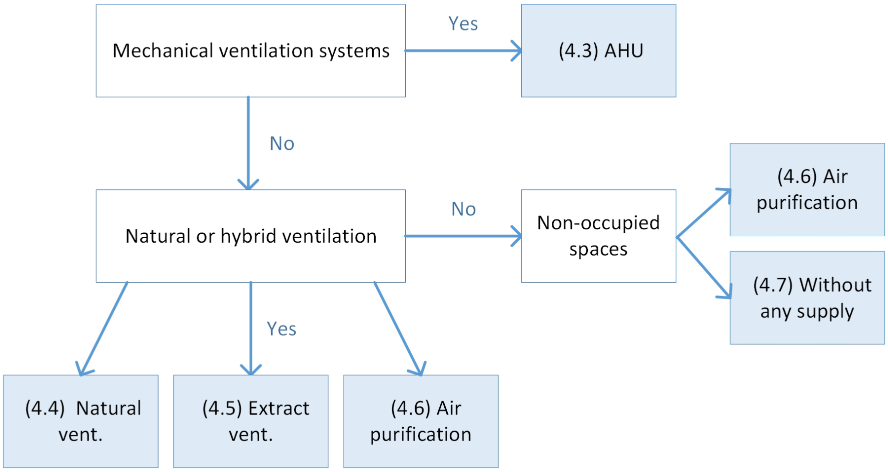


FIGURE 1 Flowchart indicating the procedure for the selection of room-based ventilation prophylaxis measures

## 4 | VENTILATION AND AIR PURIFICATION

### 4.1 | Enhancing measures against indirect infections

Morawska and Milton argue that although people may think that they are fully protected by adhering to the current recommendations, "in fact, additional airborne interventions are needed for further reduction of infection risk."[36] In support of this assertion, evidence is now emerging from large cohort studies carried out in European schools, confirming the extent to which ventilation is able to reduce SARS-CoV-2 transmission in classrooms.[37,38] A consistent finding from such studies is that increasing ventilation rates has a significant impact on reducing the risk of infection, with in-classroom transmission reduced by over 80% in one study, where six air changes per hour (ACH) were used.[38] Moreover, in addition to the well-documented effect on long-range transmission[39,40,41] there is emerging evidence that room ventilation rates significantly affect short-range airborne transmission.[42]

Studies have shown that classroom $CO_2$ monitoring and teacher education are vital to ensure that teachers understand how and when to ventilate appropriately during the pandemic.[43] In well-mixed spaces, $CO_2$ serves as a reliable scalar for the ambient air flow; however, it should be noted that aerosolized pathogens are subject to additional removal mechanisms, including filtration (e.g. by face masks, filtration devices and internal circulation), sedimentation, and deactivation. Therefore, the concentration of $CO_2$ cannot be taken as an absolute measure of the SARS-COV-2 concentration or the risk of infection since this is also dependent on the probability that an infector is (or was) in the room and on the duration of exposure.[44] As such, COVID-19 indoor safety guidelines can be broadly expressed in terms of cumulative exposure to $CO_2$ under the assumption that an infected person is present in the room.[44,45]

The sensor should ideally be wall-mounted at seated head height and not located directly adjacent to an open window or too close to the occupants.[46] The lower the $CO_2$ concentration in the classroom is, above the ambient air value (approx. 415–450 ppm), the lower the respiratory aerosol exposure and associated *indirect infection* risks will be. From the point of view of indoor hygiene and viral transmission risks in a typical classroom (where masks are worn), a $CO_2$ value of 1000 ppm should not be exceeded on average over a teaching hour.[47,48] This value can be achieved, for example, by commencing purge-ventilation whenever the $CO_2$ concentration reaches approximately 1200 ppm $CO_2$ until it falls below approximately 800 ppm $CO_2$.

Such values were determined early in the pandemic, however, and on the basis of increased transmission with new (Omicron) variants, Rowe et al.[49] propose that $CO_2$ thresholds of 800 ppm (when masked) and 600 ppm (when unmasked) represent more appropriate targets. For practical reasons, maintaining such values may be difficult or impossible year-round in many existing naturally and mechanically ventilated classrooms since a $CO_2$ reduction from 1000 to 600 ppm implies approximately a threefold increase in the ventilation rate, in a typical classroom. In wintertime, maintaining thermal comfort at such high ventilation rates will carry a substantial energetic penalty. For this reason, strategies providing a base level of ventilation augmented by additional room-based air purification methods (Section 4.6) may be preferable.

Ventilation rates only influence the dilution of suspended particles, and it is important to acknowledge that there can be orders of magnitude difference in the emission rates of aerosols entering a room according to activity levels, masking compliance, and a number of other factors.[50] It should also be noted that in the absence of masks, respiratory jets from the occupants are likely to pose a substantially greater risk than the well-mixed ambient air. For this reason, ventilation systems and air purifiers cannot obviate the need for masking and physical distancing.[50,51]

Although natural ventilation has been successfully used to mitigate various airborne epidemics historically,[52,53] it is not always the most effective or acceptable solution in every educational setting. Comfortable internal temperatures can be difficult to maintain using openable windows when the outside air temperature falls below 6 °C.[54] Therefore, the selection of the most appropriate ventilation prophylaxis measure(s) for a specific room or zone within an educational building depends on a number of factors. These include consideration of the functional characteristics of the room being assessed, the occupancy patterns, and the presence or absence of existing natural and mechanical ventilation systems. Figure 1 provides a schematic flowchart to guide this selection process. A detailed commentary of the relevant issues pertaining to each ventilation (or air cleaning method) is provided in the corresponding sub-sections.

### 4.2 | Air distribution pattern in rooms

School classrooms are usually rectangular, with air volumes typically in the range of 100–300 $m^3$. During lessons, students and teachers typically remain in fixed places, so the occupant dynamics are low. Under these conditions, the risk of infection can be plausibly estimated using models that assume complete mixing of the air.[55] However, there are situations that cause directed air flows which cannot be described by such general models. These include speaking loudly,[56,57] coughing, and sneezing.[58] In addition, room-specific conditions including the type of ventilation system, the temperature of the surrounding surfaces, and the locations of individuals can have large effects on the localized distribution of aerosols.[59] For example, it has been shown that exhaled air jets can travel further in rooms using displacement ventilation than in those using natural or mechanical mixing ventilation.[60]

In naturally ventilated classrooms, incoming airflows (generated from an open window) in line with a row of seated occupants, have been shown to increase the risk of infection transmission when an infected individual is seated near to the window.[59] This risk can be mitigated by using a baffle inside the open window to direct the incoming air downward to the floor, before it enters the breathing zone, which can also help reduce cold draughts during the cooler months.[61] Speaking is known to generate large amounts of aerosols, and opening one or two windows next to the teacher has been proven to facilitate the rapid exit of these particles.[62]

Studies of mechanical ventilated classrooms show that aerosol distributions are strongly influenced by the system design and layout. Properly designed displacement ventilation systems promote vertical stratification (Appendix S3, Figure A2), allowing the warm contaminated air to be removed above the breathing zone of the occupants. In contrast, mixing ventilation distributes the air throughout the space and does not provide any potentially clean zones.[63] A common finding in mechanical systems is that infectious particles disperse in the room and re-concentrate around the return ducts and filtration unit inlets.[64,65] One study, using a CFD model of a displacement ventilation system, showed that students in the back corners of the room received two to three times less particles on average than most other students in the room.[65] Such findings are difficult to generalize but highlight the benefits of computationally modeling spatial flows as a means of evaluating the optimal placement of inlet and outlet diffusers, as well as the positioning of portable room filtration units.[65,66]

### 4.3 | Air Handling Units (AHUs) and room ventilation systems

Air Handling Units (AHUs) and simple room-based ventilation systems can be used to provide a continuous air exchange and replace stale indoor air, enriched with carbon dioxide ($CO_2$) and respiratory aerosols, with fresh outdoor air. This can be achieved without necessitating the opening of windows or user interference. In view of the pandemic, the proportion of outside air should typically be set as high as possible.[67] However, several studies have cautioned that raising ventilation rates in response to the COVID-19 pandemic requires careful analysis of the growth in energy consumption to ensure indoor comfort conditions are maintained.[68,69,70] Current international standards vary in regard to what is considered an appropriate fresh air supply rate for classrooms. In the US, the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) standard 62.1-2019[71] recommends 5 L/(s·person) for classrooms and other educational facilities, while European standards (ISO 17772 1:2017, EN 16798 1:2019)[72,73] recommend an air flow rate of at least 7 L/(s·person).

According to EN 16798-1:2019,[73] there are three possible methods which may be used to determine the airflow rate per person. For example, using EN 16798-1 Method 1, one must account for the design ventilation rate per person plus the design ventilation rate for diluting emissions from the building itself. So, assuming one is designing to meet a normal (i.e. 'medium') level of occupant expectation (i.e. Category II targets, using Method 1), then 7 L/(s·person) + 0.7 L/(s·$m^2$) is needed if it is a low-emitting building. Assuming there is typically one student per 3 $m^2$ (of internal floor area), the fresh air requirement equates to 9.1 L/(s·person), that is, circa 33 $m^3$/(h·person). The lower recommendation, here, of 25 $m^3$/(h·person) represents a pro-rata adjustment for children and adolescents, but on no account should this value be further reduced.

It should be noted that the abovementioned ventilation standards were conceived prior to the COVID-19 pandemic and should therefore be interpreted as the minimum permissible ventilation requirements. In the context of COVID-19, findings regarding optimal ventilation rates for infection prophylaxis vary considerably. Research by Dai and Zhao, using the Wells-Riley equation, showed that ventilation rates an order of magnitude higher than existing European standards recommend are needed to ensure an infection probability of $<1\%$.[74] Pollozhani et al.,[69] using a modified version of the Lelieveld model,[75] demonstrated that increased ventilation rates would continue to reduce infection rates if applied at levels beyond those currently specified in European and international standards. In contrast, recent research, using a simplified model of occupant-exhaled pollutants, suggests that a ventilation rate of 10 L/(s·person), in line with current recommendations proposed by the WHO, provides a similar viral concentration vs distance decay profile to that found in outdoor settings.[42] This finding should be treated cautiously since it is based on a theoretical room with a negligible pressure gradient and a simplified steady-state jet model of expired aerosols.[76]

The implications of infectious organisms being recirculated in school ventilation systems were first highlighted almost 50 years ago during a measles outbreak in an elementary school in upstate New York.[77] In situations where an AHU uses recirculated air, this must be effectively filtered[78] either by using HEPA-grade filters (E10 to H14 according ISO 29463-1[79]) or by combining coarser filter classes ISO ePM1 (50) and ePM1 (80), (commonly referred to as F7 and F9 filters). Filter upgrades should be undertaken in collaboration with an HVAC professional to ensure the AHU is able to overcome the additional pressure drop induced by the new filters. Properly installed, maintained, and operated air-handling systems can effectively reduce the risk of indirect infections and provide good indoor air quality and comfort beyond the pandemic (Appendix S3). Currently, however, only about 1 in 10 European schools possess dedicated air-handling systems.[80]

### 4.4 | Natural ventilation (via openable windows)

A simple and easily implemented means of removing respiratory aerosol and airborne viruses from indoor spaces can be provided by the use of openable windows (i.e. natural ventilation). Natural ventilation remains the most widely used ventilation method in European school buildings.[80,81]

Purge ventilation is a manually controlled process, whereby rooms are ventilated at a relatively high rate to rapidly dilute pollutants and refresh the stale indoor air. This can be achieved by opening the windows fully and should take place in classrooms at a 20-min interval (or less) for about 5 min' duration during the pandemic. Purge ventilation should also take place during breaks between classes (e.g. using the 20-5-20 rule).[67,82] Ventilating only during the breaks is insufficient to maintain the hygienic targets ($CO_2$ concentration) compatible with COVID-19 prophylaxis.[83]

An empirical monitoring study of a naturally ventilated Korean classroom demonstrated that using continuous ventilation with a reduced opening area (ratio of the opened window area to the maximum openable window area) can be as effective as purge ventilation. In a double-sided (i.e. cross-ventilation) configuration, with a 15% opening area, it was possible (even during the summer months) to achieve 6.51 ACH (on average), while a single-sided configuration, with a 30% opening area, yielded 3.28 ACH (on average). At these air-change rates, it was determined that the infection probability in the classroom could be maintained at <1% and 2% (respectively) by restricting the exposure time to <3 h and wearing a mask.[84]

In practice, the duration of ventilation required for a complete effective air change is dependent upon the number, size, and position of the window openings as well as the building design and the outside temperature. In cold weather, air exchange generally takes place within a few minutes; thus, the duration of ventilation during lessons can be shortened (to approx. 2–3 min), which is advisable in order to minimize adverse effects on thermal comfort (Appendix S2). Only during warmer periods, when external air speeds are low and indoor and outdoor air temperatures are similar, is rapid air exchange impaired. This can be countered by varying the length of purge ventilation periods across the day in accordance with the outside temperature. In summer, continuous ventilation (either through tilting bottom-hung windows or by leaving side hung windows ajar) can help reduce respiratory aerosol exposure in addition to the use of intermittent purge ventilation.

Estimating natural air exchange rates (AERs) through window openings or via other means (ventilation grilles, passive ducts systems etc.) is an expert task which can be implemented using the formula provided in the European standard EN 16798–7:2017,[85] or in industry guidance documents such as CIBSE AM10.[86] It should be noted that natural ventilation flow rates vary significantly not only from season-to-season but also from minute-to-minute in response to changing pressure differentials across ventilation openings and are typically higher the greater the temperature difference is between the internal and external air mass.[87] For this reason, ventilation adequacy is most easily verified using a carbon dioxide ($CO_2$) sensor to continuously monitor and display the $CO_2$ concentration.[63] This device should preferably incorporate (or be connected to) a display providing easily recognized visual alerts, such as a traffic light warning system, corresponding to defined $CO_2$ thresholds (Section 4.1), indicating when windows need to be opened.[88]

Regular natural ventilation, which can be continuously verified by $CO_2$ measurements, ensures effective removal of respiratory aerosols.

### 4.5 | Extract ventilation systems

Extract fans (sometimes referred to as exhaust fans) are well-established as a means to supplement natural ventilation in a variety of contexts, including occupational health and safety,[82] and have previously been shown to decrease the concentration of indoor-generated pollutants in classrooms.[89] When applied as a retrofit measure, they are typically installed on the inside of the window-pane, below the ceiling level, where they actively extract the polluted room air from the classroom, while at the same time, fresh make-up air flows in passively from the outside, via an open window or inlet vent.

Extract fans reduce the indirect risk of infection by effectively removing respiratory aerosols and can also ensure good indoor air quality and a comfortable indoor environment beyond the pandemic. When used in conjunction with extract hoods located above the occupied zone of a classroom (Appendix S3, Figure A2) displacement (i.e. vertical laminar), airflows can be generated, thereby enhancing airborne viral extraction before it can circulate in the room.[90,61] Moreover, studies have shown that the use of hybrid ventilation in conjunction with appropriate control strategies can result in considerable HVAC energy savings by using natural forces when they are sufficient, but with mechanical assistance when necessary.[91,92] Extract fans can be retrofitted in naturally ventilated rooms at short notice and at relatively low cost.[93] Installation must be carried out professionally, particularly with regard to the power supply and controls, in the interests of avoiding accidents and fires. Depending on the targeted ventilation requirements and system dimensioning, extract fans can be run either intermittently or in continuous operation (Appendix S3).

Extract fans provide a well-established means of maintaining the fresh air supply and ensuring the effective removal of respiratory aerosols year-round.

### 4.6 | Mobile and room-based air purifiers

Mobile air purifiers can also help reduce aerosol particle concentrations and thus indirect infection hazards. Curtius et al. showed that the aerosol concentration in a classroom was reduced by more than 90% within <30 min when running four HEPA purifiers in tandem, with a clean air delivery rate (CADR) of 5.5 $h^{-1}$.[94] However, mobile air purifiers have the fundamental disadvantage that they do not lead to a renewal of the room air. They can, therefore, only serve as an additional supportive measure to reduce the aerosol-borne risk of infection but cannot replace other measures such as ventilation and mask-wearing.

In order for mobile air purifiers to be used, it is essential that their effectiveness, with regard to reducing virus contamination in a real room, is independently verified according to official standards, such as the German norm VDI EE 4300-14[95] (established under the direction of the German government to provide independent and verifiable measurement standards for mobile air purifiers). This is a critical point since Küpper et al. found that the CADRs in real settings can be significantly lower than those determined in standardized test chamber experiments, which they attributed to the differing size distributions between actual and standard test aerosols used in some international standards.[96] In addition, air purifiers must be appropriately sized, properly set up, correctly installed, and operated,[97] while a number of authors have emphasized the need to replace or clean the filters with a frequency higher than that indicated for ordinary use.[97,98] Moreover, filters need to be disposed as medical waste, or thoroughly disinfected, to prevent secondary contamination.[98] Similar to AHUs and extract fans, the operational noise pollution and draughts from mobile air purifiers must also be taken into account and kept to a minimum (Appendix S2).[94]

Mobile air purification units that do not remove viruses through filtration but inactivate them in the air (e.g. UV-C irradiation, plasma field ionization, etc.) can also be considered. Accidental exposure is a major challenge for devices deploying conventional 254-nm germicidal ultraviolet (GUV) light since it is known to cause sunburn-type reactions, while long-term exposure is linked to photocarcinogenesis.[99] In contrast, research has shown that Far-UVC (222 nm) does not induce acute reactions in the skin or eyes nor delayed effects such as skin cancer and has been shown to efficiently inactivate the *Staphylococcus aureus* bacteria.[100] On the basis that previous studies, using a broad range of Far-UVC wavelengths, have shown comparable surface inactivation of SARS-COV-2[101] and airborne human coronaviruses (OC43 and 229E),[102,103] it is likely that Far-UVC will also be proven effective against SARS-CoV-2. In the context of classrooms, UV-C devices have the major advantage of being silent, but unlike mechanical systems with air filters, they do not lead to a reduction in fine dust pollution in the room. The use of UV-C devices is not yet established in schools however, and it must be convincingly demonstrated that occupant exposure levels do not exceed the ICNIRP guideline limits.[99] A further concern arises in relation to the photochemical activation of a wide range of molecules present in the indoor environment (e.g. VOCs) by UV-C light, which could potentially cause health effects, even in low concentrations. Precise test specifications for UV-C secondary units can be found in the German norm DIN-TS 67506 TS[104] and for other types of mobile air purifiers in VDI EE 430O-14[95] (for which there are currently no international standard counterparts). The use of independently tested air purifiers can help reduce the risk of indirect infections in classrooms with limited ventilation, for example, in Category 2 rooms (Appendix S4) as defined by the German Environment Agency.[48] In practical terms, this applies to any room where the $CO_2$ concentration cannot be significantly lowered (to 800 ppm or below) within a short period of time even with the windows open. This includes rooms with restricted window openings and where windows are not opened regularly due to factors such as excessive external noise.[48]

Room sterilization via the nebulization of active ingredients such as hydrogen peroxide ($H_2O_2$) and hypochlorous acid (HOCl) is an established procedure for the disinfection of hospital operating theaters. These substances are strong oxidizing agents with correspondingly high electrochemical potential. In principle, such substances are suitable for use against bacteria, fungi, and viruses. However, the repeated use of mechanically nebulized $H_2O_2$ and HOCl in indoor rooms in which people live, work, and study is not established. The German Federal Environment Agency (UBA) and the Robert Koch Institute (RKI) have strongly advised against spraying these substances in normally occupied indoor spaces. The release of other oxidizing agents such as chlorine dioxide ($ClO_2$), hydroxy radicals (OH), and ozone ($O_3$) is also considered questionable. Uhde et al.[105] conclude that such disinfection measures in occupied indoor spaces remain impractical, while harboring potentially serious health risks.

The operation of mobile air purifiers can significantly reduce transmission risks but does not replace the need to ventilate and wear masks in the classroom. Attention should be given to minimizing noise from filtration systems and to the risk of hazardous byproducts arising from room sterilization systems.

### 4.7 | Intermittently occupied rooms and rooms without effective fresh air supply

Occupied rooms in school buildings in which there is no possibility of ventilation at all are not suitable for teaching and cannot comply with international standards for ventilation.[71,73] Mobile air purifiers do not provide a suitable means of enabling the permanent use of these rooms. This is because mobile air purifiers, as described above, do not provide an exchange between the indoor and outdoor air, and consequently the general indoor air quality in the room will deteriorate over time as a function of the occupancy.

The situation is different in poorly ventilated corridors, storage rooms, and bathrooms that are only intermittently used. Here, retrofitted extract air systems or mobile air purifiers can help improve the situation. Special consideration should be given to bathrooms however since toilet flushing is known to facilitate the spread of pathogenic organisms, including SARS-CoV-2.[106] In this regard, mitigation actions (including advice to use toilet lids when flushing) coupled with increased air flow rates (and/or additional air purification measures) are imperative.[107]

## 5 | CONCLUSION

By combining the above-mentioned prophylactic measures to create a "layered strategy" and by consistently implementing and monitoring them, the risk of infection from classroom-based teaching in schools can be significantly reduced. Evidence shows that mask wearing alongside social distancing and ventilation can create a strong trifecta effect in reducing both long- and short-range infection risks inside classrooms. Ventilation methods that meet or exceed current international guidelines for the provision of fresh air and the removal of contaminants via natural or mechanical ventilation are fundamental to this approach, but their successful implementation requires continuous $CO_2$ monitoring and due consideration to thermal and acoustic comfort criteria. Mobile air-purifiers can significantly augment the benefits of ventilation, but they cannot replace the aforementioned trifecta. Emerging technologies such as Far-UVC are likely to provide significant further prophylactic benefit once their safe deployment in classrooms has been established and have the added benefit of not increasing the heating demand.

The risk of infection changes with the introduced viral load and has to be reassessed regularly with regard to the general infection incidence and in relation to the emergence of new viral variants. Therefore, regular testing and contact tracing are needed to inform the appropriate implementation and fine-tuning of the prophylaxis measures. The precise level of infection or morbidity risks which are considered acceptable, in the context of keeping schools open, must be continually re-evaluated in relation to both the educational benefits and the wider impacts on society as a whole. The multi-layered strategy of infection prophylaxis, presented here, can be readily adjusted in accordance with the overall effectiveness, compliance with the core protective measures (masks, ventilation, and distancing), and the need for additional measures such as testing, vaccination, and contact reduction.

## AUTHOR CONTRIBUTION

**Robert McLeod:** Conceptualization, Methodology and Writing—Reviewing and Editing. **Christina J. Hopfe:** Conceptualization, Writing—Original Draft and Writing—Reviewing and Editing. **Eberhard Bodenschatz:** Conceptualization and Writing—Original Draft. **Heinz-Jörn Moriske:** Conceptualization and Writing—Original Draft. **Ulrich Pöschl:** Conceptualization and Writing—Original Draft. **Tunga Salthammer:** Conceptualization, Writing—Original Draft and Writing—Reviewing and Editing. **Joachim Curtius:** Writing—Original Draft. **Frank Helleis:** Writing—Original Draft. **Jennifer Niessner:** Writing—Original Draft. **Caroline Herr:** Writing—Original Draft. **Thomas Klimach:** Writing—Original Draft. **Martin Seipp:** Writing—Original Draft. **Thomas Steffens:** Writing—Original Draft. **Christian Witt:** Writing—Original Draft. **Stefan N. Willich:** Writing—Original Draft.

## CONFLICT OF INTEREST

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## DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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