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Ventilation strategies to reduce airborne transmission of viruses in classrooms: A systematic review of scientific literature

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ABSTRACT

The recent pandemic due to SARS-CoV-2 has brought to light the need for strategies to mitigate contagion between human beings. Apart from hygiene measures and social distancing, air ventilation highly prevents airborne transmission within enclosed spaces. Among others, educational environments become critical in strategic planning to control the spread of pathogens and viruses amongst the population, mainly in cold conditions. In the event of a virus outbreak – such as COVID or influenza – many school classrooms still lack the means to guarantee secure and healthy environments.

The present review examines school contexts that implement air ventilation strategies to reduce the risk of contagion between students. The analysed articles present past experiences that use either natural or mechanical systems assessed through mathematical models, numerical models, or full-scale experiments. For naturally ventilated classrooms, the studies highlight the importance of the architectural design of educational spaces and propose strategies for aeration control such as CO_2-based control and risk-infection control. When it comes to implementing mechanical ventilation in classrooms, different systems with different airflow patterns are assessed based on their ability to remove airborne pathogens considering parameters like the age of air and the generation of airflow streamlines. Moreover, studies report that programmed mechanical ventilation systems can reduce risk-infection during pandemic events.

In addition to providing a systematic picture of scientific studies in the field, the findings of this review can be a valuable reference for school administrators and policymakers to implement the best strategies in their classroom settings towards reducing infection risks.

1. Introduction

In the last two decades, humanity is confronted with three coronavirus disease outbreaks: SARS-CoV-1 (2002–2003) [1], MERS-CoV (2012) [2], and SARS-CoV-2 (2019) [3]. For every pandemic, it is important to understand the transmission routes of the infectious agent to assess suitable mitigation strategies.

The coronaviruses, like many other respiratory viruses, have three main routes of transmission: (i) short-range droplet transmission, (ii) long-range airborne transmission, (iii) infected surface contact transmission [4]. While standard hygiene measures and social distancing could prevent short-range and infected surface contact routes, air ventilation has a key role to control the airborne transmission route [5], which is the dominant one [6].

The scientific evidence shows that indoor transmission occurs more frequently than outdoor transmission [7]. Because of this, indoor environments are considered to be at high risk of contagion, and ventilation should be the first preventive measure [8]. About this, international and national agencies such as the World Health Organization (WHO), the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), and the Federation of European Heating, Ventilation and Air Conditioning Association (REHVA) have published guidelines and recommendations to prevent the spread of coronavirus (SARS-CoV-2) via airborne [9–11]. All guidelines promote the use of ventilation recommending as much outdoor air as possible, but the rate of ventilation to eliminate the risk of airborne contagion has not yet been established [12].

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Nomenclature table

ACH	Air Change per Hour
AD	Air Distribution
APS	Aerosol Particle Sizer Spectrometer
AP	Air Purifiers
AS	Aeration Strategies
CFD	Computational Fluid Dynamics
CJV	Confluent Jet Ventilation
DCV	Diffuse Ceiling Ventilation
DV	Displacement Ventilation
FSM	Full-Scale-Experiments
HEPA filter	High Efficiency Particulate Air Filter
HVAC	Heating Ventilation and Air Conditioning
IAQ	Indoor Air Quality
IEQ	Indoor Environmental Quality
IF	Intake Fraction
IJV	Impinging Jet Ventilation
MERV XX	Minimum efficiency reporting values XX
MM	Mathematical Model
MV	Mixing Ventilation
MVS	Mechanical Ventilation System
NDIR	Non-Dispersive Infrared
NM	Numerical Model
NVS	Natural Ventilation System
OPS	Optical Particle Counter
PE	Personal Extraction
PIV	Particle Image Velocimetry
PV	Personal ventilation
RQ	Research Question
SV	Stratum Ventilation
UFAD	Under Floor Air Distribution
UVGI	Ultraviolet Germicidal Irradiation
VP	Ventilation Procedures
VR	Ventilation Rate
WAV	Wall Attachment Ventilation

In school buildings, the implementation of these guidelines has entailed many difficulties, forcing lessons to be held online and/or with the windows open even in cold conditions, to the detriment of indoor environmental quality (IEQ) among students and teachers. Even before the SARS-CoV-2 pandemic, several national and international research projects such as the SEARCH project (School Environment and Respiratory Health of Children; 2006–2013) [13], the SINPHONIE project (Schools Indoor Pollution and Health—Observatory Network in Europe; 2010–2012) [14], and the InAirQ project (Transnational Adaption Actions for Integrated Indoor Air Quality Management; 2016–2019) [15] have reported low levels of indoor air quality (IAQ) and poor ventilation in school buildings.

The lack of adequate ventilation, in countries characterized by cold winters, is because teachers tend not to open the windows to avoid creating thermal discomfort among students.

As a matter of fact, school classrooms in winter are centres for the spread of diseases such as influenza, the most common virus responsible for acute respiratory illness among school-age children [16]. Influenza viruses share the same routes of transmission as coronaviruses [17], and indoor air ventilation is a suitable way to reduce the risk of infection too [18], as can be seen by comparing the spread of influenza before and after the implementation of the anti-contagion measures dictated by the COVID-19 pandemic [19]. The severity and size of influenza viruses vary from year to year [20] causing sick leave among students which has an economic impact with the related direct and indirect costs (medical visits, diagnostic investigations, hospital admissions, drugs, and parental absenteeism from work) [21].

Hence, promoting acceptable indoor air changes in school environments has proven to bring many advantages to students. Yet, a great extent of the educational stock built before the approval of thermal conditioning regulations in the Mediterranean area lacks mechanical ventilation systems (MVS), only relying on natural ventilation system (NVS), which stands as a scarce strategy to guarantee healthy and productive environments.

To this aim, the present research sets within two research projects developed in Italy and Spain, aimed at sharing experiences and outcomes towards inter applicable ventilation strategies to improve the quality of Mediterranean school environments. In Italy, a doctoral fellowship co-funded by Politecnico di Milano and the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA by its Italian acronym) pursues to investigate and promote a national strategy for equipping existing school buildings with innovative MVS that will aim, amongst other aspects, to counteract the transmission of viruses. In Spain, the research project COHEVES (Retrofit ventilation strategies for healthy and comfortable schools within a nearly zero-energy building horizon), funded by the Spanish Ministry of Science and Innovation (with reference code PID2020-117722RB-I00) and developed by TEP 130 from the University of Seville, has amongst its aims the diagnosis of current environmental performance of existing schools and the assessment of ventilation strategies for their improvement in light of EU nZEB targets and 2050 decarbonized cities.

In this regard, the present paper aims to provide a review of past experiences found in literature concerning the definition of ventilation strategies to avoid airborne transmission of diseases in existing school buildings. After the collection of related studies on the topic, a screening process and selection of those within the scope of the paper a review has been done by answering two main research questions (RQs) listed in Table 1. The novelty of this article resides in the collection and classification of the results from case-study experiences that implement ventilation strategies in the context of the school environment, the assessment of the obtained outcomes and, on the bases of these, the outline of recommended actions to be implemented in school classrooms to limit the risk of contagion.

The paper is structured as follows: Section 2 provides an overview on the topic background delving on the methods used to assess airborne transmission of pathogens, the types of air contagion risk mitigation and the main characteristics of air distribution systems; Section 3 describes the methodology used to develop this review, in particular the search strategy, the screening process, and the synthesis method; Section 4 presents the outcomes found on the reviewed articles; Section 5 displays a discussion on the main results; and Section 6 discloses the main conclusions and potential lines of research.

Table 1
RQs employed in the screening phase of reviewed works.

No.	RQs	Logics behind the question
1	Which ventilation strategies were used or designed to reduce airborne transmission in school environments?	To indicate realized studies and their outcomes.
2	Which benefits have these ventilation strategies?	To assess the effectiveness of different ventilation strategies.

2. Background overview

2.1. Risk assessment methods for airborne transmission of respiratory diseases and related indices

In the scientific literature, several evaluation methods on the risk of cross-infection can be found. These can be grouped in mathematical methods, numerical methods, and full-scale experiments methods.

2.1.1. Mathematical methods

Among the mathematical methods there are the dose-response model and the Wells-Riley model [22], which are used as quantitative evaluation methods of the airborne infection risk. But, since the dose-response model needs costly information, such as particles size and infectivity, the Wells-Riley model is more frequently used [23]. The Wells-Riley model uses the concept of quantum of infection (the number of infectious airborne droplets required to infect a person) to evaluate the probability of infection P (%) based on the Poisson probability distribution as can be seen in Eq. (1):

$$P = \frac{C}{S} = 1 - e^{-\left(\frac{I \cdot q \cdot p \cdot t}{Q}\right)} \tag{1}$$

where C is the number of infection cases, S is the number of susceptible people to be infected, I is the number of infectious subjects, q (quanta/h) is the quanta generation rate, p (m^3/h) is the pulmonary ventilation rate, Q (m^3/h) is the VR of the space, and t (h) the time of exposure. The quanta emission rate q of a specific virus depends on the expiratory activity of the infectors (i.e., breathing, speaking, etcetera). Many studies have been carried out to calculate the q for SARS-CoV-2, leading to very different results [55], including [24], where q was calculated based on the viral load present in the sputum. The assumption of well-mixed air, the steady-state condition, and the absence of other airborne pathogen sink mechanism (filtration, deposition, and disinfection) represent the major limitations of this model. Therefore, over the time, this model has undergone various modifications, including the one proposed by Gammaitoni-Nucci [25], where the steady-state condition is eliminated, and other influencing factors are added, ending in Eq. (2):

$$P = 1 - e^{-\frac{p \cdot I \cdot q}{V}\left(\frac{N \cdot t + e^{-N \cdot t} - 1}{N^2}\right)} \tag{2}$$

where V (m^3) is the volume of the room and N (h^{-1}) is the total disinfection rate, which considers the effect of ventilation, filtration and deposition mechanisms as reported in Ref. [56]. However, the well-mixed air assumption remains, thus this last model is unable to evaluate airborne transmission risk spatially and temporally.

To overcome this limitation [23], proposes a dilution-based evaluation method, while [26] proposes the use of the exhaled air volume fraction to estimate the number of q that people could re-breathe. With this last model, the spatial variation of risk infection could be obtained by dividing the room into multiple zones [22].

Regardless of the mathematical model adopted, the acceptable individual risk P_{max} should be chosen to avoid any infection event (basic reproduction number of infections $R_{event}<1$). R_{event} is the ratio between the number of infection cases (C) and the number of infectious subjects (I), seen in Eq. (3):

$$R_{event} = C/I \tag{3}$$

If S is known, the acceptable probability of contagion can be calculated assuming a given number of infectors, as in Eq. (4):

$$P_{max} < I/S \tag{4}$$

Assuming only one infection subject in the environment ($I = 1$) [27], suggest to take as a reference value a probability of contagion of $P<0.1\%$ for indoor environments up to 1000 people, while $P<1\%$ for indoor environments up to 100 people. Therefore, the greater the number of people gathered, the lower the acceptable individual risk should be.

Although the mathematical models are a simple and quick assessment method for infection control strategies, the role of ventilation in controlling airborne spread of pathogens is not limited to the ventilation and filtration rate alone, but also to airflow direction and airflow patterns [18,28]. These influencing factors cannot be considered by mathematical models, but additional numerical and full-scale experiments are needed.

2.1.2. Numerical methods

The airflow in enclosed environments can be described by a set of differential equations (Navier-Stokes equations) [29]. For simplified assessments, these equations can be solved analytically, while for detailed analysis, it is necessary to use a numerical method that will reformulate these equations into a high number of ordinary equations to solve them, as computational fluid dynamics (CFD) do. Hence, CFD-based simulations are able to calculate fluid motion and heat transfer using numerical approaches and can solve a range of problems related to laminar, turbulent, and multiphase flows [30]. Through the CFD simulations it is possible to evaluate the ventilation effectiveness based on the task of the ventilation system e.g., removal of pollutants, removal of heat, or supply fresh air to the breathing zone (the area immediately surrounding individual's nose and mouth where most of the air is drawn into their lungs) [31].

As reported from Ref. [32], CFD become a tool for the modelling of disease transmission in buildings after the 2003 SARS epidemic, and it is particularly used to improve hospital ward ventilation. For the investigation of airborne transmission between people, it is necessary to insert computational thermal manikin(s) in the space geometry and model the dispersion of respiratory droplets and pathogens released by respiratory events [33]. For this type of applications, it is therefore necessary to carry out multi-phase simulations, where the transport and the trajectories of the pathogen droplets can be described with both a Lagrangian and Eulerian approach [34]. Various methods can be found in the literature by which the risk of cross-infection of different airflow patterns has been investigated.

For an overall analysis of the cross-infection risk in the considered space, the index local mean age of air τ_{mean} (mean value of residence time of local air) can be obtained by solving the following partial differential equation Eq. (5) as reported by Ref. [35]:

$$\frac{D(\rho\tau_{mean})}{Dt} = \frac{\partial(\rho\tau_{mean})}{\partial t} + \frac{\partial(\rho\tau_{mean}u_i)}{\partial x_i} = \rho \tag{5}$$

Where D is the material derivate, ρ is the air density, t is the time, and x is the location.

Some authors, instead, use simply a spatial-temporal distribution analyses of exhaled pathogen particles [36,37] to assess high and low risk zones of exposure defining a risk index I_{risk} of the type in Eq. (6):

$$I_{risk}(x) = \sum p_i(x) \tag{6}$$

where $\sum p_i(x)$ represents the total number of particles that pass at a given point x over the entire simulation. With this type of analysis, it is usual to look at the evolution in time and space of the particles in the breathing zone, and evaluate their concentration, path-lines, and the average residence time (defined as the average time that particles, once exhaled, take to be removed). Although these parameters are useful indicators to evaluate the airborne pathogen removal effectiveness of different airflow patterns, they provide general information for the assessment of the risk of cross-infection. Therefore, specific exposure risk indices were developed based on the concentration field. The exposure risk index (ε_{ex}), defined by Eq. (7), uses the pathogen particle concentration in the breathing zone of a susceptible individual as indicator of infection risk [38].

$$\varepsilon_{ex} = \frac{C_{di} - C_{ds}}{C_{de} - C_{ds}} \tag{7}$$

where C_{di}, C_{ds}, and C_{de} are the particle concentration in the breathing zone of the susceptible, at the ventilation supply, and at the ventilation exhaust. Another exposure index is the intake fraction (*IF*), which is defined as the proportion of exhaled particles mass from the infected individual that is inhaled by the exposed individual [39], seen Eq. (8):

$$IF(t) = \frac{\int_0^{t_{in}} C_{in}(t) M_{in} dt}{\int_0^{t_{ex}} C_{ex}(t) M_{ex} dt} \tag{8}$$

where $C_{in}(t)$and $C_{ex}(t)$are the inhaled concentration of the exposed person and the exhaled concentration of the infected person at time t, while $M_{in}$and M_{ex} are the flow rates of inhaled flow of the exposed person and exhaled flow of the infected person. $t_{in}$and t_{ex} are the exposure time of the exposed person and the respiratory duration of the infected person.

2.1.3. Full-scale experiments methods

In full-scale experiments, physical measurements are carried out directly onsite, which can alternatively be recreated, as often happens, in laboratories or special test rooms equipped to simulate the experimental conditions. The studies on airborne pathogen transmission involve the use of real thermal manikins (to create the thermal body plume) [40] or human volunteers to recreate realistic scenarios and perform flow and particle transport analysis in the surrounding of the manikins or the volunteers. In Ref. [33] the main experimental measurement techniques are reported. The flow techniques use the schlieren imaging method [41] to measure the velocity field of human expiratory activity using particle image velocimetry (PIV) [42]. Although they are useful for providing understanding of expiratory flows, they provide no quantitative estimates of the risk of cross-infection between people, and they are generally used to provide a detailed validation database for droplet propagation of expiratory activity in CFD simulation [43].

In aerosol techniques, instead, aerosol generator machines are used to simulate expiratory flows. Thanks to these machines it is possible to generate particles of various sizes in order to study the influence of dimensions in airborne transmission. The dispersion pattern and the concentration of the aerosols could be measured through optical particle counters (OPC) or aerosol particle sizer spectrometers (APS), that when positioned near the mouth of the exposed manikin allow to evaluate the exposure risk indices (ε_{ex} and IF) under different airflow pattern [44,62]. In other studies, the measures obtained by this instrumentation are used, through mathematical function based on particle mass balance, to evaluate the decay rate or residence time of the particles generated in the indoor environment, and thus evaluate the airborne particle removal effectiveness of different airflow patterns [45] or air filtration devices [46].

Among the experimental methods, the most used remains the tracer gas technique. As for numerical methods, it is possible to evaluate the local mean age of air τ_{mean} too, by relying on this approach. In this case, it can be done by using the surveyed data onsite through Eq. (9) [47]:

$$\tau_{mean} = \frac{1}{C(0)} \int_0^{\infty} C_p(t) dt \tag{9}$$

where $C(0)$ is the initial tracer gas concentration and $C_p(t)$ is the concentration at a certain point in the room at time *t*.

Moreover, as reported by Ref. [48], tracer gas is a suitable surrogate of exhaled droplet nuclei for studying airborne transmission in the built environment since airborne transmission of viruses (long-range route) is characterized by small droplets (3–5 μm) which have aerodynamics closer to a gas. Furthermore, tracer gas simulations are less complex, and no assumption or simplification are required for the modelling, thus it is easier to obtain reliable results. According to this, to simulate the exhaled virus droplet nuclei from the source manikin, breathing thermal manikins [49] are needed, while the tracer gas concentrations could be monitored and measured via a set of fast gas concentration meters [50] to evaluate the exposure risk indices (ε_{ex} and IF) [51,52].

2.2. Mechanical ventilation systems and infection control strategies

MVSs have repeatedly been regarded as potentially responsible for the spread of infectious agents [18], and in some cases, it has been shown to blame [53]. These systems can be used as a primary infection disease control measure (e.g., hospitals), but if not adequately designed can contribute to airborne transmission of viruses [54]. In summary, they could prevent the risk of infection through three main principles [55]:

- **Air ventilation**: ventilation dilutes air contaminant concentration in confined spaces by indoor-outdoor air exchanges. However, also air direction and airflow patterns have a key role to prevent cross-infection between occupants.
- **Air filtration**: the virus particles are physically removed by passing through one or more filters. Air filtration can be achieved either by installing filters as components of the MVS or by placing portable air purifiers in the room. High efficiency particulate filters (HEPA) are widely used since they can remove particles emitted by human exhalation greater or equal to 0,3 μm with 99.97% efficiency. Their high efficiency, however, entails high fan energy costs, therefore a good trade-off between risk reduction and costs is represented by filters with minimum efficiency reporting values (MERV) of at least 13. MERV 13 can capture airborne viruses with a filtration efficiency of 70% for 0.3–1 μm particles [56].
- **Air disinfection**: it consists of the inactivation of viruses. A popular technology is that based on ultraviolet germicidal irradiation (UVGI) through portable devices for naturally ventilated spaces. This technology, installed inside an MVS does not produce pressure losses like filters do.

After the advent of the COVID-19 pandemic, many studies have defined operations and interventions to adopt in buildings equipped with a centralized MVS. The general idea is to have a flexible system that can diversify its operation, acting in one way during pandemics and in another way during normal situations [57]. During pandemic events, the system should guarantee the possibility of increasing the air flow and count with back up filters to be activated. The heat recovery system should be disabled if it involves air contamination, e.g., rotary heat exchangers, at the expense of thermal comfort and energy saving. Air recirculation between different rooms should be deactivated, otherwise a filter with an efficiency at least equal to MERV 13 should be positioned. Indeed, air filtration is more effective in lowering the aerosol concentration than increasing the outdoor air fraction [58]. Moreover, the inlet diffusers should be positioned in such a way that they do not favour air flows from one person to another [59].

2.3. Air distribution system and cross-infection

Air distribution strategies can be subdivided into total volume air distribution, where there is room-scale ventilation, or personalized ventilation, where air is supplied locally to each occupant directly to the breathing zone. In Ref. [60], the authors critically reviewed the main air distribution strategies. The ones cited in the reviewed literature of this paper are highlighted below:

- **Mixing ventilation system (MV)**: the air is supplied with high velocity to achieve a well-mixed air condition in the indoor environment, thus using a dilution principle to reduce the concentration of air pollutants.

- **Diffuse ceiling ventilation system (DCV)**: the air is supplied from the ceiling and extracted either from the ceiling or at the floor level sideways. The air pattern is similar to the one of MV, with the difference that the air is supplied by large opening inlets through which the air enters the occupied zone at low speeds and without a precise direction.
- **Displacement ventilation system (DV)**: the air is supplied at slightly lower temperatures than the ambient one (typically a difference of 3–4 °C) at floor level and it is taken from the ceiling. In this way, a thermal stratification of the air is generated, vertically removing air pollutants from the occupied area thanks to the thermal gradient.
- **Under floor air distribution system (UFAD)**: the air is supplied through a plenum located between the structural slab and the underside of a raised floor and it is extracted from air diffusers located in the countertop. The principle of removal of pollutants is similar to that of DV, with the difference that the air is supplied at higher speeds through a greater number of diffusers.
- **Stratum ventilation system (SV)**: the air is supplied and taken out through diffusers positioned in the vertical walls at the height of the occupied area on the two opposite sides of the room. In this way a horizontal flow is generated which supplies clean air directly to the level of the breathing zone.
- **Confluent jet ventilation system (CJV)**: the air is usually supplied through various ceiling linear slot diffusers and sucked at floor level. The set of air diffusers generate a uniform flow at moderate speed which carries pollutants and heat from top to bottom.
- **Personal ventilation system (PV)**: the fresh air is supplied directly to the breathing zone of occupants through small diffusers located near each occupant, usually sat in benches or chairs. In this way the quality of the inhaled air of each occupant is implemented, and it is also possible to adjust the speed, direction, temperature, and rate of ventilation according to the preferences of each individual. This system can be combined with the personal extraction system (PE), where an extraction system is added to reduce the spread of exhaled airborne particles.

Many studies have addressed the problem of airborne virus transmission by analysing the influence of the air distribution system in the diffusion of respiratory particles in different configurations, using both CFD simulation and full-scale test room. In offices with 10 people, PV seems to be the best solution to avoid cross-infection, followed by DV, SV and, while MV and DCV have the worst performance [61]. However, different types of PV devices and different orientations between the occupants, bring to different levels of exposure [62], especially when the infector uses PV devices, without PE, and there is an increase on dispersion of exhaled droplets [63].

Furthermore, systems that generate vertical ventilation, like DV and UFAD, could trap high concentrations of exhaled droplet nuclei (those larger than 10 μm tend to settle [64] in the breathing zone due to the low airspeed and the air thermal stratification, resulting in an increased exposure risk for the occupants [65–67]. Therefore, more knowledge is needed to understand the influence of factors (i.e., location of supply and return diffusers, number of people, room sizes, etcetera) that govern this unwanted phenomenon [68].

The combination of total volume air distribution strategies with PV could bring to a background dilution of exhaled particles and provide clean inhaled air for the users. Anyway, vertical ventilation systems such as UFAD and DV combined with PV reduce the intake fraction inhaled by occupants much more than MV and PV combined [69].

Hence, the type of devices and the airflow direction of PV present very different impacts [63]. Therefore, the development of MVSs for schools' classrooms will need to consider not only VRs but also the airflow direction and air distribution patterns, to prevent the designed system from promoting contagion [28].

3. Methods

A three-stage procedure was adopted for the creation of this systematic review to answer the reported RQs (Table 1). The method is structured as follows: i) a preliminary online database survey was performed through a keyword search criterion (Section 3.1); ii) irrelevant articles were discarded from the review according to the aim of this work (Section 3.2); and lastly, iii) the articles identified were classified to give an orderly structure to this article (Section 3.3).

3.1. Search strategy

Scopus database was used as the unique source, consulted until December 2021. Table 2 presents the set of search strings used to narrow down the number of papers consistently with the scope of the present research, aimed at finding ventilation strategies and ventilation devices that dealt with airborne transmission of viruses in school environments.

At first, the research strategy was defined so that the documents found concerned studies carried out exclusively in school environments where one or more ventilation strategies were analysed as mitigation strategies. Thus, a keyword search (TITLE-ABS-KEY) was used, connecting the words with Boolean operators "AND" and "OR". The research carried out using the strings listed in Table 2 identified a total of 317 documents. Then, the documents found were subsequently filtered to i) consider only documents that presented a high level of scientific analyses ("Article" OR "review article"), and ii) were published in peer-reviewed journals ("Journal"). As a result, 271 documents were identified.

3.2. Selection process

Once 271 documents were identified, the selection process reported in Fig. 1 was used to select articles relevant to this study. In the screening phase, where 205 records were discarded by analysing their title and abstract. In this first phase, many medical articles were discarded (144), where epidemiological and clinical investigations were proposed in the school environment. Other reasons for discarding were the analyses of non-school-building contexts, the study of contaminants other than viruses, and analyses focused on thermal comfort. The remaining 66 articles passed to the second phase, named eligibility, where only documents proposing and analysing one or more ventilation strategies were selected. In the last phase, named affinity, articles that did not provide useful information to evaluate the proposed ventilation strategies and studies concerning occupational strategies, desk shields, face

Table 2
Documents found on Scopus database.

Boolean operator	String (Title-Abs-Key)	All documents	Filtered documents
AND	Classroom **OR** school **OR** educational building	317	271
AND	air handling **OR** air distribution **OR** ventilation performance **OR** hvac **OR** ventilation strateg* **OR** ventilation syste* **OR** mechanical ventilation **OR** forced ventilation **OR** demand contro* ventilation **OR** displacement ventilation **OR** mixing ventilation **OR** ventilation retrofit **OR** CFD **OR** computational fluid dynamics **OR** air filt* OR air condition*		
AND	viral load **OR** airborne transmission **OR** airborne infection **OR** virus transmission **OR** cross-infection **OR** infection risk **OR** aerosol **OR** covid		

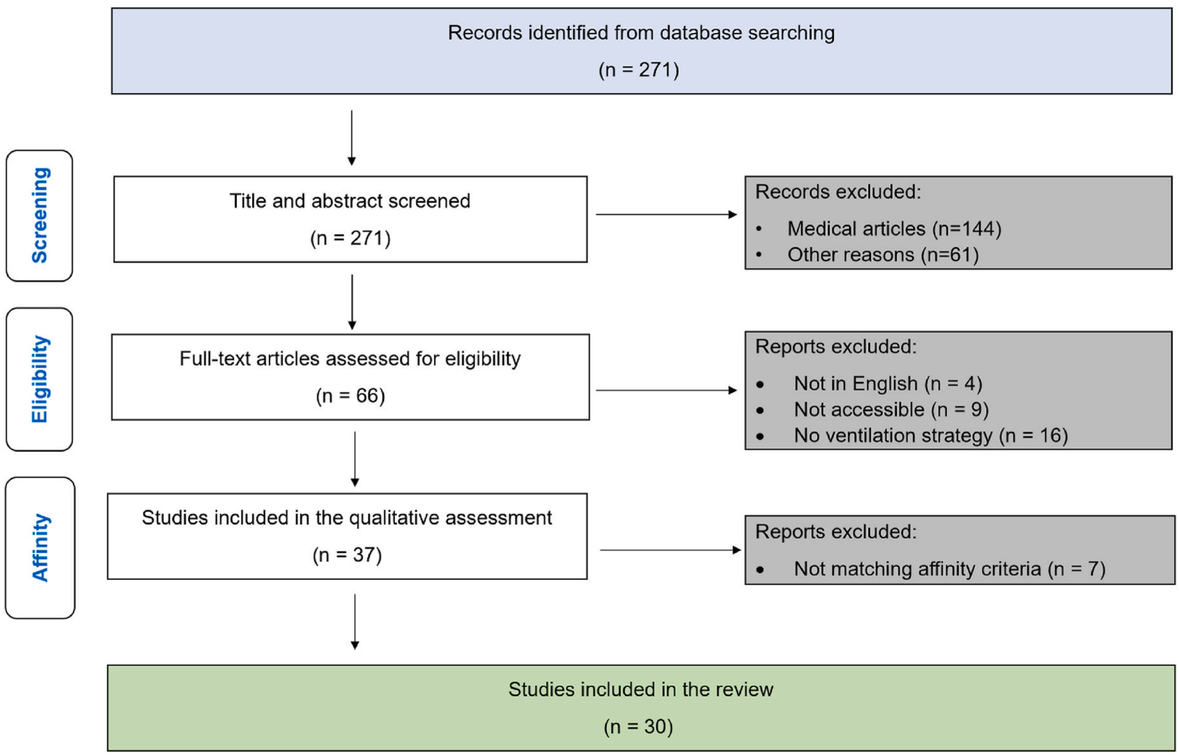

Fig. 1. Flow chart of the selection process.

mask, or other mitigation strategies were discarded.

3.3. Synthesis method

The articles included in this review analyse and propose one or more ventilation strategies to be applied in school buildings, evaluating their effectiveness in reducing airborne transmission of viruses through one or more assessing methods, i.e., mathematical model (MM), numerical model (NM), and full-scale experiments (FSM). The analysed sample of papers was sorted into two main categories regarding the ventilation system adopted or simulated in the classroom setting of the studies:

- Natural Ventilation System (**NVS**)
- Mechanical Ventilation System (**MVS**)

Then, a set of sub-categories were drawn in relation with these two main groups:

- Aeration Strategies (**AS**)
- Air Purifiers (**AP**)
- Ventilation Procedures (**VP**)
- Air Distribution (**AD**)

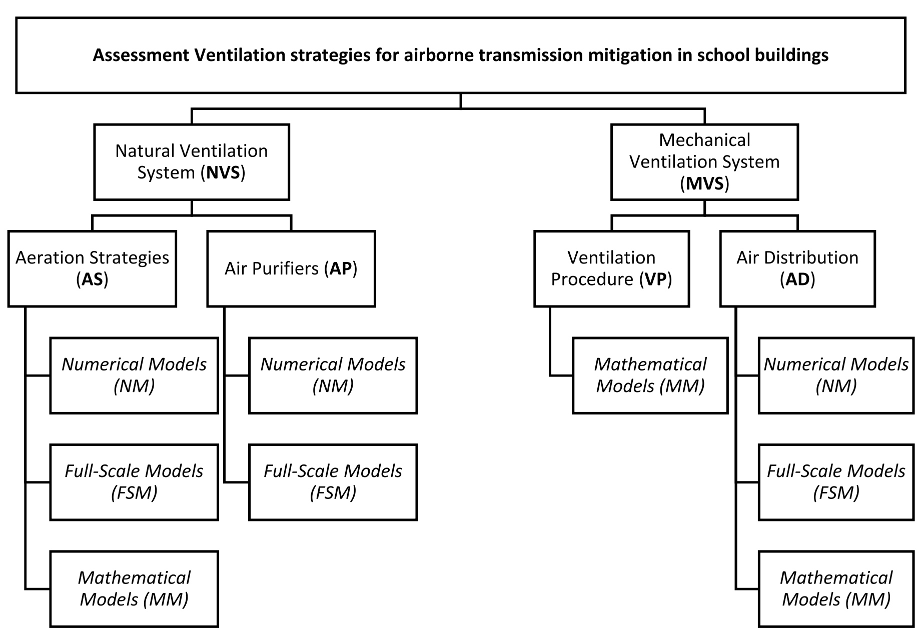

Fig. 2. Groups and sub-categories of the collected articles.

As can be seen in Fig. 2 AS concern natural ventilation strategies as well as AP, as it has been commonly found in the reviewed literature, whilst VP and AD concern mechanical ventilation strategies. In the AS category, studies have been included when the risk of contagion with manual airing or fan-assisted ventilation is investigated considering the three assessing methods, while in AP there are studies that have tested AP devices either installed in real classrooms or through numerical simulations. In the VP category the studies are included when various strategies that can be adopted with MVS to control infections are evaluated, based on VRs and/or filtration rates, through mathematical models. Finally, in AD there are studies concerning the airflow pattern of MVSs, therefore CFD simulations are usually used to evaluate the effectiveness of infected particles removal of several air distribution systems. Table 3 reports the classification of each article and the assessment method used in them to evaluate the infection risk of the proposed ventilation strategies. It must be noted that in some cases, more than one method was used.

4. Results

In this section, the findings of the 30 studies included in the present review, are reported clustered according to Fig. 2 flowchart. The section is first divided into two sub-sections: natural ventilation strategies (Section 4.1) and mechanical ventilation strategies (Section 4.2). Then, both sub-sections have been sorted according to the subsequent categories defined in the synthesis method: aeration strategies (Section 4.1.1), APs (Section 4.1.2), ventilation procedures (Section 4.2.1), and air distribution systems (Section 4.2.2). Some studies cut across more than one category and are therefore referred to in more than one section.

4.1. Natural ventilation strategies

In this section, 12 articles are reported concerning naturally ventilated school classrooms, 7 of which regard aeration strategies and were assessed through mathematical model or CFD simulations (both in some cases), while 5 studies regard the use of APs in school classrooms and were all evaluated through CFD simulations or full-scale experiments.

Table 3
Number of documents for each group.

Ref.	Ventilation system	Strategy type	Mathematical method (MM)	Numerical method (NM)	Full-scale experiment (FSM)
[70]	NV	AS	x		
[71]	NV	AS	x		
[72]	NV	AS&VP	x		
[73]	MV	VP	x		
[74]	MV	VP	x		
[75]	MV	VP	x		
[76]	NV&MV	AS&VP	x		
[77]	MV	VP	x		
[78]	MV	VP	x		
[79]	MV	VP	x		
[80]	MV	VP	x		
[81]	NV&MV	AS&AD		x	
[82]	MV	AD		x	
[83]	MV	AD		x	
[84]	MV	AD		x	
[85]	MV	AD		x	
[86]	MV	AD		x	
[87]	MV	AD		x	
[88]	MV	AD			x
[89]	NV	AP			x
[90]	NV	AP			x
[91]	NV	AP		x	
[92]	NV	AP			x
[93]	NV	AP		x	
[94]	NV	AS	x	x	
[95]	NV	AS	x	x	
[96]	MV	VP	x	x	
[97]	MV	AD	x	x	
[98]	MV	AD		x	
[99]	MV	AD		x	

4.1.1. Aeration strategies

In [70], the authors analysed the risk of infection in a naturally ventilated school in Suwon (Korea) during the spring season, using a mathematical model (Wells-Riley equation). The tested classes have an area of 64.6 m^2 and a volume of 168 m^3 and are equipped with windows along two parallel sides thanks to which it is possible to carry out single-sided or cross ventilation. The authors evaluated the risk of contagion assuming the presence of only one infected person, according to different windows opening rate (15%, 30%, and 100%) with and without face masks. The results show that the risk of contagion after 3 h of lessons, without masks, is closer to $P = 1\%$ only with cross ventilation (100% of open window ratio with 22.4 ACH), while the use of the masks allows to reduce the opening of the windows to 15% (6.5 ACH and $P = 0$, 98%) and 30% (11.2 ACH and P = 0,57%). Instead, in the case of single-sided ventilation, with 15% (2.1 ACH) and 30% (2.9 ACH) of windows opening ratios, not even the use of masks can keep the risk of contagion under the unit, with respective values of 2.50% and 1.94%.

In [94], the impact of windows design on airflow distribution and infection probability was investigated using CFD simulation and Wells-Riley equation in a naturally ventilated classroom with cross ventilation. Although various configurations of window opening are simulated with 1.6 ACH, contagion risks remain between 35% and 70%. By integrating low-cost fans into the windows at the height of 1.1 m, the risks of contagion decrease, ranging between 10% and 20%.

In [81], it is shown how, the presence of an infected student in a classroom who sits near an open window can give rise to the horizontal propagation of infected particles and therefore to the infection of another student. To prevent this phenomenon, the authors suggest either keeping the door open and opening the windows only at the top or using deflectors that direct the flow of air entering the window downwards. In these ways it is possible to prevent the particles exhaled by the infected student from being propagated to the height of the breathing zone.

In this regard, in Ref. [95] different settings of airflow deflectors applied on external windows were analysed in a classroom. Combining CFD simulations and the Wells-Riley equation, the authors report that by installing 90-degree deflectors on the external windows the infection probability decreases by 19.3% (from 41% to 21.8%) when the source is located in the middle of the class not in line with the window, while installing 45-degree deflectors reduces the infection probability by 17.5% (from 57.5% to 40%) when the source is located in line with the window. The authors also show how the presence of an infected source in line with a window always involves a greater risk of contagion regardless of the installed deflector.

Other authors investigated the possible use of air monitoring sensors combined with NVS. In Ref. [71], the authors present a CO_2-based aeration strategy that they have developed and tested in 9 schools. The device is a non-dispersive infrared CO_2 sensor (NDIR) which classifies the risk of contagion according to the concentration of CO_2 and detects 4 risk levels: low risk (up to 700 ppm), moderate risk (from 700 ppm to 800 ppm), high risk (from 800 ppm to 1000 ppm), and very high risk (above 1000 ppm). On the other hand [72], proposes an aeration strategy for classrooms based on CO_2 sensors combined with an infection risk model. Indeed, the authors suggest the use of a programmable control unit in which, by entering the characteristics of the classroom (i.e., volume, number of students) and the epidemiological situation, VRs could be dynamically evaluated by a risk infection function to avoid contagions.

In [76], following this line, the authors have developed an ad-hoc airing procedure for naturally ventilated school buildings based on a MM (dose-response model) to maintain $R_{event} < 1$. The manual airing cycles are defined by a control unit which evaluate the air change needed on the base of the infection risk. Subsequently, a CO_2 sensor determines the current air exchange and, if this is less than the one required, it proposes an aeration cycle by means of visual alert.

To summarise, it can be deduced from these studies that under conditions of air changes greater than 6.5 ACH the risk of contagion can be less than $P = 1\%$ if face masks are worn, while without face masks, at least 22 ACH are required to set the contagion risk under 1% [70,94]. If unable to have these air changes, the strategy to reduce the risk of contagion may be to install low-cost fans that can reduce the risk of contagion by up to 70% [94], or deflectors that can give up to 20% risk reduction [95]. As demonstrated from the other reported studies, air monitoring sensors or control units based on the infection risk can be used to manage windows opening procedures to mitigate new infection cases [71,72,76]. Table 4 reports the case studies with the relative aeration strategy tested and the evaluation parameter used.

4.1.2. Air purifiers

APs are portable devices capable of take room air, filtering it and putting it back in by recirculating clean air. Their use finds application in difficult-to-ventilate environments, and in case of NVS can constitute a valid mitigation strategy from airborne pathogens. To evaluate their efficiency, CFD simulations and/or full-scale experiments are required.

Ref. [89], adopting both the approaches, shows that the best placement point for a purifier in a classroom is at the bottom of the class centrally, with direct flow towards the blackboard, or in the centre of the long side if the air outlet is on the sides. Though these configurations, providing a filtration rate of 5.4 h^{-1} enables a 90% of aerosol to be removed after about 26 min, while with rates of 3.5 h^{-1} the aerosol concentration is reduced by 30% and by 50% after 25 and 60 min respectively, as carried out by the full-scale experiment reported in Ref. [90]. [91] also simulates an AP placed in the bottom of the class through CFD, setting 6 h^{-1}, and highlight how the airborne particles reduction strongly depends on the infector position.

Through a full-scale experiment in a testing room, the removal of aerosols of several settings of an AP equipped with HEPA filter was compared with the one obtained through different ventilation conditions (no ventilation, single-sided and cross natural ventilation, and a MV system which supply 17.6 ACH) [92]. The room was set up as a classroom, and the experiment measured, through an OPS, the number of particles present in the breathing zone of a susceptible positioned in the row of benches following the one where the infected source was positioned (simulated by an aerosol generator). The experiment showed that both with a filtration rate of 17.6 h^{-1} and 11.7 h^{-1}, the AP removed more particles than the tested air ventilation systems. Moreover, CFD simulations of a low-cost box fan air cleaner equipped with a MERV 13 filter in a school classroom show that beyond a certain VR (from 2 h^{-1} to 5 h^{-1}) only filtering brings further benefits [93]. The authors show that the best removal efficiency is obtained when the AP is positioned close to the infected. Hence, as a recommendation, positioning purifiers near possible fan coils or at several points in the class would ease a better distribution of the clean air.

Hence, as highlighted in these studies, it has been demonstrated that APs' performance is better than that of air renovation from outdoors: the volume of air filtered by an AP indicates a greater removal of particulate matter than the one achieved by renovating the same volume with new air from outdoors [89,92,93]. Nevertheless, also the relative position of the AP and infected person can influence the AP performance [90,91, 93]. The studies concerning APs are listed in Table 5.

Table 4
Aeration strategies case studies.

ref.	Method	Room volume	N. students	Aeration strategy	Evaluation parameter
[70]	MM	168 m^3 (8.20 × 7.90 × 2.60)	NA	Single-sided ventilation and cross-ventilation with different windows opening ratio	Probability of infection
[94]	NM/MM	595 m^3 (14.00 × 8.50 × 5.00)	40	Cross-ventilation with different windows opening and integrated fan	Probability of infection/ Particles concentration
[81]	NM	216 m^3 (12.00 × 6.00 × 3.50)	10	Different positions and heights of the windows	Particles concentration
[95]	NM	595 m^3 (14.00 × 8.50 × 5.00)	NA	Cross-ventilation with different window airflow deflectors	Probability of infection
[71]	MM	11 classrooms 112–155 m^3	5–21	CO2-based aeration	CO2 concentration
[72]	MM	150 m^3	NA	Risk infection-based aeration	Probability of infection
[76]	MM	150 m^3 (50 m^2 × 3 m)	NA	Risk infection-based aeration	Probability of infection

NA - data not available.

4.2. Mechanical ventilation strategies

The mechanical ventilation strategies found in literature are mainly assessed both with CFD simulation and MMs. As reported in Ref. [97], in a classroom equipped with a common DCV system using the Wells-Riley based equation the risk of contagion is underestimated, with an average of about 30% respect the results obtained through the CFD model. The same article also reports that the likelihood of being infected varied individually among students by up to 220%, mainly due to local air flow distribution, and secondly due to the distance from the infected source. In Ref. [81] the authors show how the well-mixed air conditions, used in the most of MMs, brings to an estimate of aerosol concentration in the breathing zone level up to 50% minor than the CFD simulation case carried out in a classroom equipped with a conventional DCV system. By the way, in Ref. [77], a new method is proposed to determine the risk of contagion which, unlike the Wells-Riley model, can determine the risk of contagion also based on the distance of susceptible individuals from the infected source. The authors demonstrate that for an exposure period of 90 min the risk of contagion for individuals closest to the infected subject is 1.3 times higher than that calculated with the Wells-Riley equation, and which decreases by about 65% by increasing the distance from 1.5 m to 3 m. In Ref. [78], instead, a distance index and an air distribution system efficiency index are proposed to be integrated in the Wells-Riley model. Thanks to these indices, the authors demonstrate that it is possible to reduce VRs compared to those obtained with the model proposed by Wells-Riley. Thus, as reported from Ref. [97], MMs could be a useful tool to quantitatively assess the infection risk reduction of ventilation strategies in classrooms, where VR and filtration rates, exposure time, and class volume are the typically used parameters.

This section is aimed at pointing out the different outcomes that are achievable by using each assessment method. Section 4.2.1 includes 8 papers regarding ventilation procedures to control the infection risk, that can be adopted in classroom when a MVS is present. Section 4.2.2 instead, concerns 9 studies focused on the performance of different air distribution systems in the airborne pathogens removal through CFD simulations.

4.2.1. Ventilation procedures

Ref. [73] have tested the impact of different intervention strategies with a MM like increasing the VRs, implementing air filtration, hybrid learning (i.e., part of the students attends lessons at home reducing the number of students in presence), and combined strategies through a

Table 5
AP case studies.

ref.	Method	Room volume	N. students	Filter type	air filtration	air cleaner position	evaluation parameter
[93]	NM	150 m^3 (10.00 × 5.00 × 3.00)	8	MERV 13	4.80	Various	Particles concentration
[92]	FSM	68 m^3 (6.40 × 4.10 × 2.60)	2	HEPA	17.6/11.7/8.8	In front of/behind the students	Particles concentration
[89]	FSM/NM	186.40 m^3 (9.40 × 6.50 × 3.05)	22	HEPA	5.40	Various	Particles decay rate
[91]	NM	197.37 m^3 (11.17 × 5.70 × 3.10)	18	carbon filter + HEPA	6.00	Behind the students	Particles concentration
[90]	FSM	222 m^3	15	HEPA	3.50	Behind the students	Particles decay rate

scenario-based analysis, with which it was possible to estimate the number of infected people attending schools. Based on the pandemic scenario assumed, implying a greater presence of infected people during the winter, and considering an air rate equal to 2 h^{-1} as a reference, the authors estimated a probability of contagion equal to 6.8% in winter and 3.8% in summer. A set of 1433 schools (prekindergarten, elementary, middle, and high schools) across the U.S. were selected as case studies. The mitigation strategies, in increasing order of benefit, were:

1. 100% of ventilation increase (from 2 h^{-1} to 4 h^{-1}).
2. 50% students online.
3. Use of MERV 13 filters.
4. 50% students online +100% of ventilation increase.
5. MERV 13 + 100% of ventilation increase.
6. MERV 13 + 50% students online +100% of ventilation increase.

The first outcome pointed out by the authors is that all the mitigation strategies proposed bring to lower infection risk in prekindergarten (below 1%, except strategies 1 and 2 in the winter season) and elementary schools than in the others, due to the lower human pulmonary respiratory rates of pupils aged 3 to 11. In the other school grades, strategies 4 and 5 have the same infection risk (about 1.5%–2% during the year), as strategies 1 and 2 (about 3%–5% during the year). In strategy 3, MERV 13 filters were simulated as higher efficiency filters leading to a slight reduction in the risk of contagion compared to the latter scenario, highlighting that using filters more efficient than MERV 13 is not cost-effective. Implementing MERV 13 filter resulted in a 30% reduction of contagion with respect to ventilation increase or 50% online students. However, apart from prekindergarten, the only strategy able to reduce the infection risk below 1% in the other school grades is strategy 6. Finally, the authors tried to increase VRs beyond 4 ACH noting a reduction in the risk of contagion. Despite this, increasing ventilation beyond 6 ACH brings little benefits, therefore promoting very high VRs alone does not mean having a low risk of contagion. For this reason, complementary strategies such as filtration should be used in schools both to maintain a low level of contagion and low energy costs.

In Ref. [96] the authors have evaluated the infection risk of several mitigation strategies (i.e., mask covering, mechanical ventilation, AP, and desk shields) in elementary classroom and high school classroom by combining CFD simulations and the Wells-Riley based equation. From the analysis of the results, the use of masks is the most efficient strategy followed by the adjustment of VRs (from 3.4 h^{-1} to 7 h^{-1}), while the desk shields have a low effectiveness. The lowest chances of infection ($P \rightarrow 1$) are achieved by combining the use of masks, an MVS, and AP. The authors highlight that in the elementary setting, due to the low pulmonary and viral emission rate of young students, the infection rate is lower than those evaluated with the adoption of several mitigation strategies in the high school settings, therefore suggesting that the risk of airborne virus transmission should be analysed by differentiating the grade of school.

Ref. [74] evaluate and compare different mitigation strategies with a systematic approach, considering building, room, and personal scale through a MM. Among the various scenarios considered, three different classroom settings were analysed: i) K-12 classroom with a volume of 396 m^3 (35 students) and 2.1 VR; ii) small college classroom with a volume of 154.5 m^3 (25 students) and 3.6 VR; iii) large college classroom with a volume of 600 m^3 (96 students) and 3.4 VR. These baseline scenarios that imply 25% of outdoor air fraction were then implemented through single and combined ventilation strategies, among which the following:

1. Different outdoor air fraction (50%, 75%, and 100% of outdoor air).
2. Increase VR (50%more supply air and double supply air).
3. Use of partitions for the students.
4. Use of MV, DV, and PV (taking into consideration the different efficiency of air distribution through a specific coefficient).
5. Use of MERV 13 or HEPA filter.
6. Use of AP or UVGI.
7. Use of face masks.

The authors conclude that to obtain a $R_{event} < 1$ in these classroom settings to the strategy should combine all the following: double the VR, use DV with partitions, use HEPA filter, and use AP and UVGI.

The same authors highlight the importance of thinking on different scales when choosing a mitigation strategy. In fact, given the numerous uncertainties that characterize the analyses of the risk of contagion in confined environments, it would be preferable to work first on the building or room scale to guarantee a generalized reduction of the contagion. Subsequently, if this is not possible or if the risk of contagion is to be further reduced, strategies are planned on a personal scale. The authors also warn that the combination of several mitigation strategies is not always advantageous. As it can be seen from the results in Table 6, using 100% external air, or using HEPA filters produces the same reduction in the risk of contagion. Hence, equipping the MVS with HEPA filters, if possible, will be more economically advantageous. Once a HEPA filter has been applied, using 100% of external air does not produce any benefit, but only energy consumption, so to reduce the risk of contagion we can increase, at least, the total airflow.

[75] provide a cost-benefit review of some main ventilation control strategies considering effectiveness, effective scale, capital cost, durability, and accessibility:

- Upgrading filters is a simple and economic operation, but it requires a replacement every 6/12 months depending on the base of the filter type, and an increase in fan energy due to the increased pressure rise through higher-rating filters.
- Increasing outdoor air supply does not require any installation of new components, but results in extra energy consumption, higher than that of upgrading filters, depending on the volume of the building to be served.
- Installing a new air distribution system (such as DV and PV) has a high initial cost depending on the scale of the system and requires

Table 6
Some mitigation strategies and related infection risk reduction and cost scale [74].

Mitigation strategy	Scale	Infection risk reduction	Cost
100% outdoor air	building	−27%	high
Doubled supply	building	−37%	high
HEPA filter	building	−27%	medium

careful planning but offers the possibility of increasing the efficiency of the ventilation system and therefore to reduce the VRs.

Ref. [72] highlights how difficult it is to avoid contagions in small-volume classrooms, strongly recommending the installation of MVSs in these cases. In historical school buildings, on the other hand, since they enclose classrooms with heights of up to 5 m, it is possible to think of installing air quality sensors connected to the windows, given that architectural constraints often limit invasive design solutions. In any case, they suggest a dynamic control of ventilation based on the risk of contagion. In this regard [76], propose to determine the VRs to be provided to mitigate the risk of airborne transmission of viruses (SARS-CoV-2 and influenza). Using the mass balance equations of a virus and CO_2, and considering the volume of the class, infected individuals, and the total number of students, it is possible to calculate the air exchange rate so that no contagion events occur ($R_{event} < 1$). This method can be applied to both mechanically ventilated and naturally ventilated schools, butCO_2 sensors are needed.

Ref. [79] simulates the installation of an air handling unit in a naturally ventilated classroom. The decentralized system can supply from a minimum of 8 l/s per person, under normal conditions, guaranteeing an average level of IAQ up to 32 l/s per person in the event of a pandemic emergency. The authors then evaluated the probability of contagion with varying air flow rates and mask filtration efficiency. Since the goal is to keep a reproduction number (R_{event}) under the unit, the authors show how this goal is achieved in the following cases: for 8 l/s per person with 95% of filtration efficiency, for 16 l/s per person with 75% of filtration efficiency, and for 32 l/s per person with 50% of filtration efficiency.

The MM could also be used to assess the energy cost of ventilation strategies to mitigate the risk of infection in schools. In Ref. [80], the annual energy cost of HVAC systems was calculated to keep the risk of contagion below 1% for American schools. Increasing the VRs alone would lead to an increase of about 6 times the National energy expenditure of HVAC (considering the one related to 2018), which is equivalent to providing a VR of about 5 ACH for prekindergarten, 10 ACH for elementary schools, and 20 ACH for middle and high schools. Using MERV 13 filters alone, instead, reduces this increase to 4 times. The use of MERV 13 filters involves the reduction of VRs, in particular 2.5 ACH for prekindergarten, 7.5 ACH for elementary schools, and 17 ACH for middle and high schools. The authors therefore suggest that the combination of MERV 13 and improved VRs could be an economical strategy in kindergartens.

To sum up, some authors argue that MVS strategies in school environments should be adapted to the school grade [73,96] and their implementation is highly encouraged in small-volume classrooms [72]. Many authors converge that to reduce cross-infection in different classrooms, MVS strategies should use HEPA or MERV 13 filters and setting VRs around 6–7 ACH [73,74,96]. Further strategies for optimizing the risk reduction can be a combination of DV with partitions, APs, UVGI [74], or a combination of face masks and APs [96]. Also, CO_2 sensors can serve to estimate the necessary air exchange rate to prevent from contagion [72]. Considering the cost-effectiveness of the measures, air filters are the most economical solution [75,80]. Table 7 shows a summary of the ventilation strategies evaluated in this section.

Table 7
Ventilation procedures case studies.

ref.	Method	Room volume	N. students	Ventilation strategy	Evaluation parameter
[73]	MM	111,485 US schools	NA	VRs (4 ACH) Use of MERV 13 Combined strategies	Probability of infection
[96]	MM/NM	NA	9	VRs (3.4 ACH) Use of MERV 7 and MERV 11 Combined strategies	Probability of infection
[74]	MM	396 m^3 154.5 m^3	35 25	VRs Different air distribution systems	Probability of infection
		600 m^3	96	Use of MERV 13 and HEPA filter Use of AP and UVGI Use of facial mask Combined strategies	
[75]	MM	NA	NA	VRs Use of HEPA filter Installation of air distribution system	Cost-benefit evaluation
[76]	MM	150 m^3 (50 m^2 × 3 m)	NA	Risk infection-based ventilation	Probability of infection
[79]	MM	155.4 m^3	25	VRs Use of facial mask Combined strategies	Probability of infection
[80]	NM	111,485 US schools	NA	VRs Use of MERV 13 Combined strategies	Cost-benefit evaluation

NA - Data not available.

4.2.2. Air distribution systems

In many articles the effect of the air distribution systems on cross-infection control were analysed. With CFD simulation and FSM, authors have focused on parameters such as the age of air, the airflow streamlines, and particles dispersion and concentration of several air distribution systems.

In [88] several tracer gas experiments in a classroom with an overhead HVAC system in heating, cooling, and neutral condition were conducted. By measuring the concentrations of the tracer gas near the neck of the thermal manikins, the authors pointed out that ceiling diffusers can create thermally stratified conditions during heating that negatively interferes with the dilution of infectious agents, causing higher exposure at all locations. In this condition occupants are exposed to respiratory aerosol 5 to 6 times higher than in well-mixed conditions, while supplying cooler or neutral air can achieve good air mixing and thus an effective dilution of bio effluents. Another issue concerning temperature is pointed out by Ref. [81]. When a DCV system is in heating mode (air supplied from the ceiling), the presence of an infected individual near a cold window (poor thermally insulated) could rise dangerous situations. Since the window surface is colder than the supplied air, the flow is brought to the floor together with exhaled particles of the infector from where it rises due to the thermal plumes of the occupants carrying infected aerosol among the students.

The authors of [83] analyse the risk of airborne infection in a small classroom setting highlighting how the design of the ventilation system is essential for the removal of infected exhaled particles. Indeed, airflow patterns could generate areas with a high risk of contagion compared to others or prefer the deposition of infected particles on certain surfaces. This situation occurs for example, when using an air distribution system with air supply and exhaust terminals are placed in a single location. In a school setting, if the infected subject is the teacher, there is a general risk of contagion greater than if the infected subject is a breathing student. In this case a single air outlet located in the back of the classroom generates a greater probability of contagion, while an extraction terminal above the infected teacher produces a generalized reduction of infected particles throughout the class, confining the spread of viruses around the teacher. The authors conclude that since a validated dose-response for

COVID-19 is not available yet, in CFD simulations the risk of infection in a given location could be assessed by analysing the total number of infected particles passing through a given location throughout the duration of the simulation, also called risk index (I_{risk}).

Furthermore, many authors have investigated the performance of several air distribution systems on controlling the spread of airborne particles in classroom settings [84]. analyse the best return diffusers placement (ceiling or floor) to reduce cross-infection in a school classroom under cooling conditions, when the supply diffusers are placed on the ceiling (DCV). The authors study the age of the air and the airflow angle concluding that the scenario with floor returns has a better performance in reducing cross-infection, reducing the age of air from 1250 s to 700 s approximately. As a matter of fact, the flow distribution is more uniform, and the age of the air is minor than in the ceiling returns scenario. Furthermore, on the height of the breathing line (1.3 m–1.5 m) the horizontal airflow decreases about 20% with the floor returns, indicating a reduction in the risk of disease spread among students.

In [82], instead, the aerosol transport emitted by different students position in classroom environments was investigated. The simulated classroom was equipped with ceiling inlet and outlet diffusers with a ventilation flow of 2090 m^3/h (8.6 ACH). The authors found that a large part of particles (24%–50%) were sucked up by the outlet diffuser without settling in any surfaces, highlighting the importance of air filtration in case of recirculation system. Furthermore, the aerosol distribution is not uniform and heavily depends on air distribution system. In particular, students near the inlet diffusers had a higher number of particles sucked up than the ones near the outlet diffusers. However, if the source is centrally placed, there is a larger spread of exhaled particles, while students in the back corners receive 3 times less particles than the other students in the classroom in each scenario.

In [85] the UFAD system is compared to a conventional MV system to prevent airborne pathogen spread in elementary classroom. In this study two UFAD schemes are proposed which differ for the positions of the inlets and outlets: in the first case placed under and above the students, in the second case, placed between the students. The authors simulated the systems in a classroom consisting of three rows of double desks, placing an infected subject in the central row. The study revealed that UFAD systems better dilute the virus concentration in rows where no infected person is present than mixing ventilation systems. In the case of the UFAD system, positioning the air outlets directly above the students' heads promotes the concentration of viruses in the row with the infecting source, while lower concentrations are obtained if the outlets are on the sides of the rows. In this case the virus concentration in the analysed breathing zone decreases by 32% and 66% respectively in the first and third row compared to the average concentration in the central row. The authors conclude that the speed of the air supplied by the UFAD systems plays a fundamental role in avoiding the distribution of viruses horizontally but must also be designed considering the comfort of the occupants.

In [86,87] the authors compare the droplets dispersion in three points of a simulated classroom (i.e., teacher facing students, students near an air supply device, and students near an air exhaust terminal) under MV, DV, and SV. The droplets concentration under MV was found to be of an order of magnitude higher than that under DV or SV. Furthermore, at all points of the breathing zone analysed SV results in a significantly lower risk of infection than DV. The authors suggest that this is due to a younger age of the air and higher horizontal air velocity obtained with SV systems in the breathing zone.

The authors of [98] compare five ventilation system varying the number and the positions of inlet and outlet vents in the same school classroom (making a ventilation pattern similar to SV, one similar to DCV, one similar to DV, and two UFAD). The CFD simulations of the various distribution systems were launched with the same air speed (0.4 m/s) and the same temperature (about 23 °C) in a classroom of 30 students. Analysing the airflow streamlines exhaled particle path-lines and their residential time, the following results are reported: i) with the SV the exhaled air of 7 students takes about 1000 s to be removed and there is a maximum peak of 5000 s; ii) with the DCV the exhaled air of 7 students takes about 400 s to be removed and there is a maximum peak of 1550 s; iii) with the DV the exhaled air of 9 students takes about 200 s to be removed and there is a maximum peak of 540 s; iv) with the first UFAD the exhaled air of 26 students takes about 400 s to be removed and there is an anomalous peak of 4800 s due to the recirculation airflow; and v) with second UFAD the exhaled air of all the students takes from 1.5 s to 4 s to be removed. The second UFAD has much lower residence times than the first one as in the former the inlet and outlet vents are positioned respectively above and below each student, while in the latter there are less outlets vents. Thus, the authors show how the UFAD systems perform better than the others minimizing the horizontal mixing of the air to effectively remove the aerosols exhaled by the students.

Moreover, in Ref. [99] the authors assess the age of air of different air distribution systems in a university classroom through CFD simulations. Four ventilation systems were tested: one DCV system (ceiling square diffusers and floor return grilles, 1.3 m/s air speed), two SV systems (along the long side with wall-mounted grilles and along the short sides with wall-mounted nozzles, 1.6 m/s and 2.9 m/s air speed respectively), and one CJV system (ceiling linear slot diffusers and floor extraction grilles, 1.8 m/s air speed). In the simulations the same air flow rate was used, 2000 m^3/s, and the results show how the DCV and the CJV have a minor average age of air (88 s) than that of the SV systems (around 300 s). Furthermore, when comparing the two SV systems, the authors note that wall-mounted grilles promote slower air exchange than wall-mounted nozzles. The authors conclude that despite similar results, the CJV system performs more uniformly in the air distribution than DCV due to the vertical displacement of the breathed air, that limits the horizontal spread of aerosols.

In brief, the reviewed articles agree that the most advantageous strategies are those that generate an air displacement by setting the inlet and outlet diffusers in opposed places, such as SV [86,87], DCV with ceiling supply diffusers and floor returns [84], UFAD [85,98] or CJV [99], reducing the age of air inside a classroom and limiting the horizontal spread of aerosols among students. Attention should be paid to the air speed though so that it does not disrupt the occupants' comfort [85]. Many authors insist that inlets and outlets should be distributed throughout the whole room, avoiding their location directly above or below the students [82,85] and not placed in a single point of a classroom leading to a higher spread of infected particles [83] or generating thermally stratified conditions during heating that hinder the dilution of infectious agents [88]. The related articles are reported in Table 8.

5. Discussion

In this section a discussion of the results obtained from the reviewed articles is presented. The results collected have been analysed and intertwined to provide an overall evaluation of the main ventilation strategies proposed by the various authors that can be adopted in classrooms. In this regard, this section refers to i) classrooms with NVS, and ii) classrooms with MVSs.

5.1. Naturally ventilated classrooms

In school buildings where it is not possible to install MVSs, for economic reasons or architectural constraints, NVS can be implemented through various strategies. Classrooms equipped with windows along two parallel sides have a much greater capacity to exchange the air (cross-ventilation) than classrooms with only one windowed side (single-sided ventilation). In the first case, the complete opening of the windows could lead to very low probability of contagion (22.4 ACH, $P =$ 1.1%), and the use of masks allows the partial closing of the windows up to 15% (6.5 ACH, $P = 0.9\%$) [70]. In the second case though, too low VRs can be reached, which entail too high risks of contagion. In this type

Table 8
Air distribution systems analysed.

Ref.	Method	Classroom volume	No. Students	Air distribution system	ACH (h^{-1})	VR (l/s pp)	Air inlet speed (m/s)	Evaluation parameter
[84]	NM	157m^3 (8.40 × 7.20 × 2.60)	23	DCV	5.00	9.60	NA	Air age/streamlines
[85]	NM	177 m^3 (8.40 × 8.10 × 2.60)	30	MV	4.50	7.40	1.93	Particle concentration
				UFAD (1)			0.46	
				UFAD (2)			0.35	
[81]	NM	252 m^3 (6.00 × 12.00 × 3.50)	10	DCV	4.00	28.00	0.50	Particle concentration/ streamlines
[86]	NM	128 m^3 (6.10 × 8.80 × 2.40)	16	DV	9.20	20.40	0.40	particle concentration
				SV			0.90	
[88]	FSM	158 m^3 (6.10 × 9.30 × 2.70)	8	DCV	4.50	24.70	1.50	tracer gas concentration
[87]	NM	128 m^3 (6.10 × 8.80 × 2.40)	16	MV	12.00	26.60	NA	particles concentration
				DV			NA	
				SV			0.70	
[98]	NM	212 m^3 (7.50 × 9.70 × 3.00)	30	SV	9.60	16.10	0.40	Air age/streamlines/residential time
				DCV				
				DV				
				UFAD				
[82]	NM	243 m^3 (9.00 × 9.00 × 3.00)	9	DCV	8.50	63.00	0.39	Particle concentration
[99]	NM	220 m^3 (6.50 × 11.60 × 2.90)	20	DCV	9.00	27.50	1.30	Air age
				SV (1)			1.60	
				SV (2)			2.86	
				CJV			1.76	

NA - data not available.

of classroom, NVS alone is not sufficient to ensure a low risk, and other strategies should be considered, such as, installing APs, or integrating low-cost fans into the windows to always guarantee an adequate exchange of air when difference in temperature and pressure between inside and outside do not allow it [94].

Other authors have proposed the use of air monitoring systems combined with control units to systematize the window opening according to a function that evaluates the risk of contagion based on a MM, e.g., Wells-Riley based equation. In this way, by setting the function with the volume of the classroom, the number of students, the number of infected students (obtained from the local epidemiological trend), and other integrated parameters like social distancing it is possible to obtain VRs capable of maintaining $R_{event} < 1$. In any case, the direction of the airflow should also be taken into consideration based on the geometry of the classroom and the arrangement of the students and the windows. In fact, the presence of an infected pupil near the window could give rise to the horizontal propagation of infected exhaled particles, and therefore the contagion of another student. To limit this danger, the flow of air entering the window can be directed downwards, using deflectors, or upwards by opening only the upper part of the windows. It is also recommended to stagger the rows of benches with respect to the position of the windows [81].

If it is not possible to provide the required air flow rates in the classrooms (typically in single-sided ventilation class), the positioning of one or more APs could be a valid alternative. These devices can filter the air and remove the aerosols exhaled by the infected from the environment, however they must be used together with NVS since they cannot renew the indoor air. The removal efficiency of exhaled particles depends on the location of the infected and the purifier [91,93], and since the position of asymptomatic people is not known, it is convenient to place the purifier at the bottom of the classroom with direct flow towards the board [89]. The filtration rate must be set according to the VR that opening the windows can guarantee, the classroom volume, and the number of students.

5.2. Mechanically ventilated classrooms

Mechanical ventilation strategies should consider the grade of the school to assess the right viral emission of children and thus an ad-hoc ventilation [96]. Based on [73,74], the risk of contagion in a poor ventilated classroom (i.e., assuming 2 ACH provided by a MVS in the MM) is the highest in high schools, followed by middle schools, elementary schools, and kindergartens. This is due to the difference in human pulmonary ventilation which determines the amount of virus in aerosols exhaled by infectious people and inhaled by susceptible people. In kindergarten, indeed, the use of a MERV 13 filter could be enough to maintain a risk of contagion $P < 1\%$, while in the higher grade schools a solution could be to provide 4 ACH, use MERV 13 filters and halve the number of students in the classes. Moreover, it is noted that increase the ACH from 2 to 4 has the same benefit of halving the number of students, and once 4.0 ACH are provided the use of MERV 13 filters is equivalent to halving the number of pupils in the class. Furthermore, even if using 100% of external air has the same risk reduction as equipping the MVS with a HEPA filter, the second solution is less expensive but adequate maintenance of the filters must be guaranteed. On the other hand, if the system is already equipped with a HEPA filter, the VR can be increased up to 6 h^{-1} to reduce contagion risk. Beyond this value further benefits are not significant.

The possibility to program the MVS specifically for a class, to avoid new infections ($R_{event} < 1$), can be based on mathematical evaluation models, as reported in Refs. [76,79]. Starting from characteristic parameters of a classroom such as volume, number of students, duration of lessons, type of activity (physical activity and expiratory activity), and number of infected people (by local epidemiological trend), it is possible to calculate the VRs dynamically to have $R_{event} < 1$. The function can be extended to consider the local spread of quanta from a contagious source [77], to overcome the well-mixed condition, and integrated by adding an index of social distance and an index of air distribution effectiveness [78], to partially consider the space distribution of the students and the air distribution system type.

5.2.1. Air distribution strategies

An air distribution system should be installed to ensure as much air mixing as possible, and consequently ensure homogeneous dilution of infected aerosol concentrations. This general consideration is due to the uncertainty of the position of the asymptomatic infection, which for a given air distribution system influences the transport of aerosols [82]. More in detail, airflow patterns of specific ventilation strategies based on the removal of infected exhaled particles from the breathing zone, are discussed below.

5.2.1.1. MV. MV systems result to be the least efficient in preventing cross-infection among students due to their high level of horizontal air mixing. The concentration of droplets in the breathing zone, if compared to DV or SV, is at a higher order of magnitude [87].

5.2.1.2. DV. DV has a better ability to remove droplets than mixing ventilation does [87]. The vertical direction of the airflow allows to avoid a horizontal recirculation of the air. However, the low air emission speeds (0.2–0.4 m/s) can cause droplets to be trapped at the breathing zone depending on their size. This problem could be avoided by using higher input velocities and increasing the distance between students. In this regard, future studies are needed that analyse different combinations of inlet velocity and temperature with various student distribution schemes.

5.2.1.3. DCV. The DCV systems provide ceiling supply and floor or ceiling return. Between these two alternatives, floor return is more effective for uniform flow distribution reducing the age of air in the classroom (1250 s versus 700 s approximately) and the horizontal airflow in the breathing zone about 20% [84]. Despite this, the horizontal component of the air in the breathing zone remains too high (about 60%) and further research should optimize the number and position of extractors to reduce this percentage. In heating mode, ceiling supply could create a thermally stratified condition, therefore thermally neutral or cooled air should be supplied for an effective mixing dilution of pathogen.

5.2.1.4. SV. SV was compared with DV and MV in two papers [86,87], which analyse the respective concentrations of droplets in the breathing zone of a class. As the air is supplied horizontally and directly into the breathing zone at high speeds (0.9 m/s) droplet removal is much more effective than that obtained under MV and DV. In terms of age of air, it is convenient to position the inlet vents along the short side and use nozzle diffusers as long as they allow high air speed and thus less air stagnation in the environment [99]. However, the strong horizontal component of the airflow could result in cross-infection. Therefore, further studies should analyse the relationship between the location and the number of inlet diffusers and extractors relative to the location of the students.

5.2.1.5. UFAD. In line with the results, UFAD systems seem to be the most effective ventilation scheme in removing exhaled particles. Thanks to the vertical piston airflow (from bottom to top) and to air inlet speeds greater than the DV, the horizontal mixing of the air is missing, allowing undisturbed removal of aerosols. The best results are obtained by installing the inlets and the outlets diffusers for each student place, in order to achieve the lower values of the resilience time of the pathogenic particles [120]. If this is not possible, it is recommended not to install the outlet vents directly above the students' heads, but to position them between the occupant's group, as an outlet positioned above a student's head also draws air from neighbouring areas and could carry infected particles directly into the student's breathing area [85].

5.2.1.6. CJV. The CJV systems can be an alternative to UFAD system. Indeed, by realizing a vertical air flow (from top to bottom) a much lower age of air is obtained than that with an SV (minimum age of air 88 s against 300 s). Even if a similar age of air is achieved with DCV, CJV generate almost vertical air movements guaranteeing a vertical displacement of breathed air [99]. Compared to the UFAD, this distribution system includes floor extraction vents, and this could be a way to extract infected particles as soon as they are exhaled.

6. Conclusions

This work has reviewed the existing literature on ventilation strategies to mitigate airborne transmission of viruses in school settings. The goal was to collect and analyse existing information on the implementation of ventilation systems in classrooms. Strategies, interventions, and performance have been identified for both natural and MVSs based on the results obtained through the main assessment methods, i.e., mathematical models, numerical models, and full-scale experiments.

For **naturally ventilated** classrooms the following recommendations are proposed:

- Cross-ventilated classrooms could achieve low exposure risk thanks to their ability to guarantee high aeration rates, while single-sided ventilated classrooms generally can provide low VRs, thus the use of AP or fan-integrated windows is recommended to achieve lower exposure risk.
- As a basic strategy, classrooms should be equipped with CO_2 sensors, so that it is possible to evaluate the level of exposure based on the concentration of carbon dioxide, and to favour air changes when concentrations exceed 700 ppm (CO_2-based aeration).
- A more efficient strategy is instead to program the opening of the windows through control units based on mathematical models (risk infection-based aeration), which based on the characteristics of the class, the grade of the school, and the number of infections assesses the rates of ventilation to be guaranteed to prevent new cases of contagion ($R_{event} < 1$).
- The presence of an infected student near the open window can cause the infection of other students, so it is recommended to arrange the rows of desks not in line with the windows or to install deflectors.

In the Italian, Spanish and other similar contexts, the mentioned strategies for solving the limit of the aeration rates of NVS in schools can be adopted as a short-term emergency solution, because they are suitable for outdoor temperature conditions close to indoor temperature (i.e., during the intermediate seasons and the short portion of the summer not included in the holydays period), while the problem of thermal discomfort caused by low outdoor temperatures during winter remains. Hence, for the middle and long-term planning, to guarantee a proper control of contagions preserving thermal comfort conditions in school buildings, MVSs should be installed.

For **mechanically ventilated** classrooms, or for classrooms where MVS is to be installed other recommendations for ventilation strategies are proposed:

- During pandemic events, MVSs should be programmed to provide a risk infection-based ventilation ($R_{event} < 1$). It is recommended to consider the age of the students, as different viral emissions correspond to different ages. Indeed, in elementary and kindergarten schools there is a lower risk of contagion. The integration of Wells-Riley based equation (to consider the local spread of virus, the social distance, the air distribution effectiveness, and the epidemiological trend) should be used to program the control unit. This allows to carry out a quantitative and personalized cost-benefit analysis of various strategies (VRs, filtration rates, etc.).
- As air distribution pattern influences the airborne transmission of viruses, the installation of new MVSs in classrooms should focus on UFAD or CJV systems primarily since they have the best performance on exhaled particles removal as long as they generate a quite fast vertical airflow. This favours a quick removal of pathogens from the breathing area, avoiding their horizontal propagation.
- The other air distribution systems work following the principle of diluting air pollutants. Among these, the SV systems, supplying fresh air horizontally directly to the breathing zone at medium-high speeds, have good pathogen removal performance with low age of air but still higher than UFAD and CJV.
- In cases where the air distribution systems listed above cannot be installed for economic reasons or architectural constraints, MV and DCV systems represent the alternative. It is recommended to supply air at neutral temperature in order not to create a thermal

stratification of the air with consequent stagnation. Furthermore, placing the extraction vents at floor level reduces the percentage of horizontal flows and therefore the possibilities of cross-infection.

Summarizing, the results carried out from the mentioned studies on air distributions seem to converge that providing a quite fast vertical airflow (UFAD, CJV) or supplying air horizontally directly at the breathing zone level (SV) have the best pathogen removal performance. These outcomes have been obtained through NM and FSM analysing the spatial-temporal distribution of exhaled pathogen particles by comparing non-specific parameters of infection risk such as concentration, residence time, and air age. These indicators also provide quantitative information concerning the risk of cross-infection in classroom settings. For this reason, CFD and full-scale experiments could be a great support for the optimal design of inlet/outlet diffusers in classrooms and tailored air distribution patterns for different classroom settings. Future studies should include specific parameters such as *IF* and ε_{ex} to better assess the individual or average risk of infection. Various combinations of temperature and air inlet speed should also be analysed, so as not to create discomfort among students. Furthermore, CFD simulations could help to determine the minimum VR to guarantee a low risk of contagion depending on the air distribution system and classroom setting, and thus promote a healthy environment with minimum energy consumption related to the ventilation system.

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CRediT authorship contribution statement

S. Ferrari: Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization. **T. Blázquez:** Writing – review & editing, Visualization, Methodology. **R. Cardelli:** Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **G. Puglisi:** Writing – review & editing, Project administration, Conceptualization. **R. Suárez:** Writing – review & editing, Validation. **L. Mazzarella:** Writing – review & editing, Validation.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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