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Ten questions concerning the future of ventilation and indoor air quality in European schools

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ABSTRACT

Research about the importance of ventilation and indoor air quality in schools has attracted scientific attention for several decades. Multiple studies have identified associations between outdoor air ventilation rates, indoor air quality, and the health, well-being, and cognitive performance of students; the precise causes of which are not fully understood. More recently schools were identified as a key node of transmission in the COVID-19 pandemic. This realisation fundamentally changed the discourse around school ventilation across Europe. Despite this awareness, and the annual burden of airborne diseases (including influenza, RSV, and others) as well as the increased likelihood of further pandemics, very little progress has been made in terms of practical measures or policy changes.

This paper examines ten key questions regarding the future of ventilation and indoor air quality in European schools through the eyes of twelve European experts. By examining these multi-faceted issues in a holistic way, the work sets out to draw clear conclusions about what is needed to improve widespread air quality problems and defects in school ventilation practices across Europe. Despite inconclusive findings in some areas, the authors argue that there is sufficient evidence to act decisively to reduce the risk of short and long-term harms and to mitigate significant health inequalities.

1. Introduction

The COVID-19 pandemic fundamentally reshaped the discourse around school ventilation across Europe, elevating it from a technical building services consideration to a critical public health issue [1,2]. This shift has brought into question the continued viability of natural ventilation in school buildings and has accelerated the adoption of mechanical ventilation solutions in many schools [3]. At the same time, heightened awareness of the implications of poor indoor air quality (IAQ) has brought into focus questions concerning indoor air quality (IAQ) metrics [4] and appropriate guideline values including the use of proxy indicators (such as CO_2) [5–7].

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A growing body of evidence suggests that poor IAQ contributes not only to occupant discomfort and cognitive decline but also to health disparities among students [8], raising the question of whether it is possible to ensure safe indoor air for all European children [9]. At the same time universal thresholds for outdoor air ventilation rates and IAQ indicators remain contested [10], particularly as rising energy bills and emerging net zero carbon targets reshape design and operational priorities.

Some of the key challenges lie in identifying when supplementary source control and air cleaning measures are necessary to mitigate elevated risks, and whether natural ventilation strategies — often well perceived for their simplicity — can still meet future standards. Beyond technology, building design and occupant behaviour also play a decisive role in achieving and maintaining good IAQ [11].

Finally, retrofitting classrooms with mechanical ventilation systems or air-cleaning devices faces practical [12], financial [13], and regulatory barriers. As climate change intensifies, it will result in more intense and prolonged heatwaves and pollution episodes; as well as elevating the risk of infectious diseases and pandemics [14]. In this context it becomes essential to redefine how we ventilate our schools—balancing health protection, learning outcomes, resilience and sustainability for future generations.

This paper is based on the collective, practical and academic, experience of twelve European ventilation and IAQ experts. The authors were chosen based on their extensive expertise in the topics of ventilation and indoor air quality in the context of schools and educational buildings. In addition to their specialist knowledge, attention was given to ensuring a broad geographical representation to provide perspectives reflective of the diverse policy, cultural, and environmental contexts found across Europe.

The ten questions presented in this paper were carefully formulated to address, what the authors perceive as, the main challenges affecting the future of ventilation and air quality in European schools. The paper sets out to explore these multi-faceted issues and areas of uncertainty by addressing ten interrelated questions. The answers to these questions underpin the conclusions and will collectively shape the future of ventilation and IAQ in European schools.

2. Q1. How does indoor air quality affect the well-being and academic performance of students?

Achieving good IAQ in classrooms is essential for undisturbed learning and comfort in schools, whilst also reducing acute health symptoms and absenteeism amongst students and teachers. IAQ is affected by various pollutants present outdoors and indoors. There is insufficient information on which specific components of IAQ affect children the most in schools. However, it can be inferred, as a minimum, that the pollutants listed in the most recent WHO Air Quality Guidelines (AQGs) will contribute to health effects, at concentrations above the specified levels (see Q3) [15,16].

Frequently, proxy-indicators are used for defining classroom IAQ. Two indicators that are widely adopted to predict classroom air quality are the outdoor air ventilation rate and the concentration of carbon dioxide (CO_2) in the room air. CO_2 is widely used to assess ventilation adequacy in classrooms because it represents the dominant source of occupant metabolic emissions, and is emitted relatively constantly at rest [17]. Using CO_2 as an IAQ indicator does not account for the pollutants from outdoors or non-human sources (see Q3). Also pollutants that do not “behave” similarly to CO_2 cannot be accounted for (e.g. pollutants produced during chemical transformations). Nevertheless, CO_2 measurements can be a useful tool if users understand how they relate to IAQ and are aware of the important limitations of their use [6] and can, to some extent, be used to estimate ventilation rates in the classroom [18,19].

Numerous reviews (e.g. [20–22]) have reported associations between low outdoor air ventilation rates and adverse outcomes, such as decreased respiratory health, increased absenteeism, and diminished short-term cognitive performance (e.g., concentration, memory, speed, accuracy) but mainly based on data from studies involving adults. Although a recent review demonstrated the effects on learning and absenteeism [23], the precise mechanisms for the described effects are largely unknown, but they should not be attributed solely to the effect of CO_2. Other studies have indicated potential associations between these effects and the presence of gaseous pollutants, including volatile organic compounds (VOCs) [24] and particulate matter (PM) in classrooms [25,26]. To explain these observations Wallner et al., [27] proposed that physiological responses are disturbed in response to air pollutants, resulting in insufficient elimination of CO_2 from the blood, respiratory problems, physiological stress, and similar responses.

Alongside ventilation, thermal conditions in classrooms have also been recognized as a crucial factor affecting student well-being and academic performance [28–30]. Haverinen-Shaughnessy & Shaughnessy, [31] found that students' test scores were affected by both their classroom ventilation rate and room air temperature but noted that further studies are needed to examine the precise causes of the observed relationships, and to establish whether the results can be generalised to other climates, building types, and ventilation modes. Thermal conditions encompass not only the dry bulb air temperature (DBT) however, but also the wet bulb temperature (WBT), mean radiant temperature (MRT), radiant surface temperature asymmetries, and localised draughts. Despite the potential influence of factors such as relative humidity (RH) on respiratory health and illness-related absenteeism [32], they remain largely unexplored in relation to academic performance.

Whilst evidence directly evaluating the effect of outdoor air ventilation rates on student health and well-being remains limited, this does not mean that there are no effects, as shown, amongst others, in the review by Mendell and Heath [28]. However, it is challenging to objectively measure these outcomes, and evidence from large-scale intervention studies is lacking. Also, the associations reported in the literature are often between different health and comfort outcomes and ventilation system types or their performance rather than actual outdoor air ventilation rates [33–35]. Conversely, there is comparatively strong evidence of an association between outdoor air ventilation rates (estimated based on CO_2 concentration) and learning outcomes and absence rates [23]; which is described in detail in Q4.

3. Q2. To what extent does ventilation, and interacting indoor air quality and indoor environmental quality parameters, influence disease transmission?

Early in the COVID-19 pandemic it was acknowledged that respiratory pathogens spread as aerosols and not just by large droplets and surface contact (fomites), as originally thought [36]. This type of transmission is well established for other respiratory pathogens, including measles [37], influenza, rhinovirus, and SARS-CoV-1 [38,39].

Aerosolized respiratory pathogens pose a risk both in the near-field and the far-far field of an infected person. The former is termed ‘short-range exposure’ and results from the inhalation of high concentrations of infectious respiratory particles (IRPs) in the direct exhalation jet of an infected individual. Direct short range (i.e. droplet) transmission is traditionally thought to occur within a distance of 1 to 2 m from the infected person, but this distance can also be significantly greater [40,41]. Indirect (i.e. aerosolised) short-range exposure poses a much higher risk because of the higher concentration of aerosolized respiratory pathogens near to an infected person. Multi-route transmission modelling by Tang et al., [42] demonstrated that, even in the context of highly ventilated aircraft cabins, indirect (short and long-range) transmission accounted for over 92 % of SARS-CoV-2 transmission, whilst droplet and fomite (i.e. surface) transmission were minimal. A longitudinal study in Swiss secondary schools (during the winter of 2023/24) [43] reported similar findings. The study used a comprehensive probabilistic framework combining molecular data, epidemiological data and the genetic proximity of respiratory viruses to quantify the relative importance of different viral transmission modes in classrooms and found that proximity was only modestly associated with higher infection risk, while exposure time in shared classrooms, and suboptimal air quality showed the strongest associations.

In the near-field direct transmission risk can be effectively reduced by avoiding close contact (i.e. physical distancing) or by wearing personal protection equipment such as an appropriate filtering facepiece (FFP) mask. Long-range exposure in the far-field can be further reduced by measures that provide pathogen-free clean air, using ventilation systems and high performance mobile air filtration [44,45], improving air distribution [46], and via the use of germicidal UV-C systems [47]. These engineering solutions can somewhat reduce the risk of indirect transmission in close proximity to an infected person but only with rather low effectiveness [48].

Indoor environmental quality (IEQ) parameters such as temperature and relative humidity have been shown to potentially affect survival of the influenza virus [1] and SARS-CoV-2 [49,50]. In this context, low relative humidity (< 30 %) may increase physiological susceptibility to airborne infections [51], but overall the influence of RH on the infection risk is strongly dependent on the type of virus, the exposure time and ventilation rate [52]. More recently CO_2 has been shown (by modifying the pH of the room air) [53] to indirectly affect SARS-CoV-2 viral infectivity. However, the bandwidth for tuning IEQ conditions is generally limited by other IEQ-related requirements, such as thermal comfort.

In practical terms the risk of far-field infection is influenced by multiple factors: including the concentration of pathogens (aerosols) in the air and the duration of exposure [54], as well as individual susceptibility. The effect of pathogen dilution with clean air on the risk of infection can be estimated using a number of modelling methods. Despite some key differences, the overall consistency in the output of these models underscores their value in public health strategy and infectious disease control [55]. Variants of the Wells-Riley equation (first developed in 1978), were widely used during the COVID-19 pandemic (e.g. [3,56]). The Wells-Riley model estimates long-range exposure risks and is predicated on several key assumptions. The most important assumption is the viral emission rate from an infected person; which can vary by several orders of magnitude between individuals [57–59] and also over time, depending on the infected individual's viral load, rendering deterministic predictions highly uncertain [60].

Viral load is typically expressed in models in terms of the quanta emission rate (quanta·h^{-1}), wherein a 'quantum' is defined as the dose of airborne nuclei required to cause an infection in 63 % of susceptible persons [61]. In addition to assuming a constant quanta generation rate the Wells-Riley model, and its derivatives [62], typically assume that the room contains well-mixed air [63]. Empirical measurement and validated computational fluid dynamic (CFD) studies show that this assumption is likely to be unreliable in many cases, particularly in shallow-plan naturally ventilated buildings [64]. Moreover, the Wells-Riley model only accounts for airborne transmission and does not consider transmission through larger droplets, that settle quickly, or fomite transmission (via physical contact with surfaces). Nor does it account for differences in host immunity, age, or underlying medical conditions. Collectively, these limitations suggest that whilst such models are useful to assess the relative risks associated with specific interventions (e.g. in response to varying room ventilation rates, or the use of filtering face protection) [3,65] they are unsuitable as a predictor of absolute risk.

Several documents provide guidance on how to determine appropriate virus-free clean air supply rates with respect to respiratory infections (e.g., [44,66,67]). The air can be delivered by an appropriately designed ventilation system,[1] and the use of filtration and air cleaners can complement baseline ventilation requirements [70]. Similarly to ensuring the effectiveness of ventilation systems in reducing the risk of infection, optimising the in-situ performance of an air filtration, cleaning, or disinfection system requires careful attention (see Q9).

Classrooms are particularly challenging environments for infection transmission due to their high occupant densities. This feature increases the risk of short-range infection, and as a result, it may be unrealistic to suggest that room-level ventilation alone is an adequate mitigation strategy in the event of an airborne pandemic [71]. The continuous supply of clean air will provide better protection, as opposed to purging during breaks which may not be sufficient to address inadequate ventilation during classes [72]. High quality empirical data on infection and ventilation in schools are sparse, and more evidence is needed. Despite the difficulties associated with obtaining such data, results such as those by Buonanno et al., [73] suggest that mechanical ventilation can reduce the risk of infection and that up to 14 l/(s·person) of clean air would be required to achieve a beneficial effect. Whilst, ASHRAE Standard 241 [44] recommends 20 l/(s·person) of clean air during pandemics and outbreaks of airborne disease.

The effective design of schools and their ventilation systems, from an infection risk mitigation perspective, goes beyond the specification of optimal ventilation rates. Whilst simplified models (such as the Wells-Riley) can be used to broadly estimate the relative risk reduction associated with certain interventions, they cannot be used to optimise ventilation system design. For example, ventilation systems based on the vertical displacement of air have been shown to improve the air quality in the breathing zone of seated occupants by up to 50 % [74]. In the context of SARS-CoV-2, it has been observed that displacement ventilation can provide the most effective means of mitigating long-range transmission, since it promotes the vertical stratification of stale air and aerosols [75,76]. The optimal design of such systems typically requires the use of appropriately parameterised CFD models [64,77]. Despite the importance of ventilation design in mitigating airborne disease transmission, it is worth noting that multiple aspects of IAQ and IEQ (including thermal and acoustic comfort) need to be considered concurrently in the design of high quality school and educational facilities [78,79] (see Q7).

Long COVID is a growing concern in the paediatric population and is estimated to effect between 10-20 % of children with a history of COVID-19 [80,81]. Limited data are currently available from the European context, however it is estimated that 6 million US children are currently affected, with the prevalence of long-COVID now surpasses asthma as the most common chronic health condition experienced by American school children [82]. Zhang et al. [83] investigated the risk of long COVID following SARS-CoV-2 reinfection using hospital and health institutions data (based on 407,300 eligible children and adolescents with a first infection episode and 58 417 with a second infection episode between Jan 1, 2022, and Oct 13, 2023) as part of the RECOVER Initiative (which included data from 40 US children's hospitals and health institutions). Notably, they found that reinfection with SARS-CoV-2 was associated with more than double the risk of a long COVID diagnosis (relative risk 2·08 [95 % CI 1·68–2·59]), with a wide range of related conditions (including neurological symptoms) being significantly more common after reinfection [83]. This evidence suggests that without better prevention strategies the societal burden of Long COVID is set to grow [84].

Moving forward, it is essential that the risk of infection in schools is reduced to a minimum, otherwise children will become significant

[1] In naturally ventilated classrooms the estimation of clean air supply rates typically involves the use of steady-state or transient mass-balance calculations, based on time-series CO_2 concentrations [19]. Such calculations can involve significant measurement uncertainty [68] as well as uncertainties regarding room occupancy and individual emission rates [69]

carriers of viruses with long-term consequences for the individual and for society as a whole [85]. Even though improved ventilation has been shown to reduce illness absence [23,86], the use of additional prophylactic measures during waves in seasonal illnesses, or a pandemic (such as staying home when sick, hand hygiene and FFP masks) remains essential [2]. This goes beyond the notion that classroom ventilation is frequently lower than standard's require [9,87] and is not designed to deal effectively with airborne transmission [88].

4. Q3. Can we avoid exposure inequalities and provide safe indoor air to all European students?

Ambient air pollution levels vary greatly depending on global, regional and local influences [89,90] which can result in significant exposure inequalities at the individual level. Therefore, when assessing outdoor air quality around schools, it is important to consider the specific locality. Prior to completing a ventilation system design, the ANSI/ASHRAE Standard 62.1 [91] recommends an observational survey in the immediate surroundings of a building during the hours this building is normally occupied to identify outdoor contaminants of potential concern. This investigation requires documentation of the outdoor air quality at both the regional and local level. At the local level it includes identification of potential contaminant sources on the site and from adjoining properties including any that operate only seasonally. It is notable that such a comprehensive assessment of the outdoor air quality, during the planning stage, is not mandated in equivalent European ventilation standards [9].

Fig. 1 shows the variance in outdoor annual mean values for particulate matter less than 2.5 µm in diameter ($PM_{2.5}$) and nitrogen dioxide (NO_2) across Europe for the year 2024.[2] The corresponding statistical parameters are summarised in Table 1. It is evident that despite the significant decline in pollutant levels, the WHO AQG values [15] (red dashed lines in Fig. 1) are still exceeded across most of the European Union (Table 1) [92]. Note that the limit values set out in the current EU Directive 2008/50/EC (as amended on 18 September 2015) for $PM_{2.5}$, NO_2 (green dashed lines in Fig. 1) and other air pollutants, significantly exceed the WHO's AQGs. However, the European Parliament has decided on a further reduction of the limit values for 2030 (EU Directive 2024/2881, adopted on 23 October, 2024) [93].

Table 1
Statistical parameters of validated outdoor annual mean values (2024 calendar year) for $PM_{2.5}$ and NO_2 in Europe. Source: European Environment Agency [94], https://www.eea.europa.eu/en/analysis/maps-and-charts/.

Parameter	$PM_{2.5}$	NO_2
Min (µg/m^3)	1.2	0.1
Max (µg/m^3)	50.3	100.8
Median (µg/m^3)	9.4	14.4
Upper quartile (µg/m^3)	13.0	21.2
Lower quartile (µg/m^3)	7.6	9.0
EU Standard (annual) (µg/m^3)	25	40
WHO Standard (annual[2]) (µg/m^3)	5	10
Total number of stations	2223	3557
Stations with annual mean > EU Standard	27	72
Stations with annual mean > WHO Standard	2104	2464

Numerous studies report relevant concentrations of particulate matter, NO_2 [95], ozone (O_3) [96], black carbon, trace metals, ammonia (NH_3) [97], formaldehyde (HCHO) [98], etc. in both urban [99,100] and rural areas [101]. Complex atmospheric chemistry driven by O_3 and other reactive gases makes the situation more complicated [90].

Multiple ambient emission sources and processes can contribute to air pollution in the proximity of school buildings, with local infrastructure having a significant impact [102,103]. Climate change related events, like wildfires [104] and extreme floods [105], can trigger further IAQ issues such as long-range particle transport [106] (see Q10). Mould growth, which previously received little attention must also be considered [107,108]. In order to assess the risk of indoor radon exposure, it is important to assess the soil composition on site [109].

Potential sources of gaseous and particulate pollutants in the classroom include students and teachers themselves [17,110] and their activities, building products, furnishings and equipment [111], cleaning products [112], laser photocopiers [113,114], as well as secondary products resulting from indoor chemistry [115]. This can cause a dilemma, where on the one hand pollutants that have accumulated in the classroom must be ventilated out; but on the other hand, the outside air may be too polluted for direct air exchange [116], without considering some form of filtration.

Studies such as SINPHONIE [87] and ImpAQS [9] have shown that there is still widespread evidence of exposure inequalities, health issues

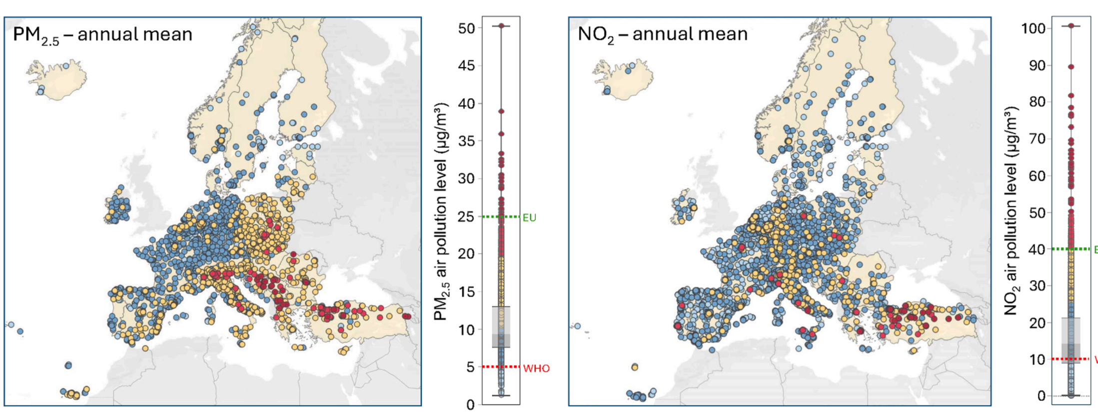

Fig. 1. Validated outdoor annual mean values (2024 calendar year) for $PM_{2.5}$ and NO_2 in Europe. Each point on the maps represents a measuring station (urban or suburban; rural, industrial, or traffic). The boxes in the Box-Whisker plots indicate the interquartile range (IQR) with red dashed lines showing the respective annual WHO AQG value and green dashed lines showing the respective annual EU limit value. Map design: © OpenStreetMap (CC BY-SA 2.0). Source: European Environment Agency [94] https://www.eea.europa.eu/en/analysis/maps-and-charts/.

and inadequate learning conditions affecting students and teachers in European schools. Although a common educational policy framework exists across Europe, the financial resources available to schools vary considerably and are influenced by socioeconomic factors and national policy priorities. Combined with school management practices and

[2] Note that 24-hour AQG values also apply to $PM_{2.5}$ (15 µg/m^3) and NO_2 (25 µg/m^3) concentrations. These are assessed at the 99th percentile of the annual distribution (i.e. allowing 3–4 exceedance days per year).

government funding mechanisms, this means that not all schools have the same budgets, leading to the potential for inequalities between regions. Furthermore, the quality of school buildings and their ventilation systems is far from uniform across Europe [87]. This reflects a complex interplay of devolved regulatory frameworks, regional practices, climatic considerations, as well as poorly harmonised standards for health and sustainability. While some still relatively small number of schools benefit from modern building techniques and advanced ventilation systems, others continue to face challenges that can severely impact the indoor environment and thus negatively impact health and educational outcomes. Decisions are still far too often based on short-term economic considerations, neglecting long-term health and wider implications (see Q8).

In view of ongoing urbanization, poor outdoor air quality and climatic changes (see Q10) as well as the progressive tightening of air quality guidelines [15], the need for technically supported solutions will increase. There are sufficient tools and guidance available to determine whether direct manual or mechanically assisted indoor/outdoor air exchange is feasible, or whether air cleaning is necessary. The Copernicus Atmospheric Monitoring Service (CAMS) of the European Union [118] offers good support for decisions as to whether a direct exchange between indoor and outdoor air is acceptable. CAMS enables online access to current data and short-term trends of regulated and unregulated pollutants for precise geodetic coordinates. However, there is an urgent need for source control beyond the smoking ban and mandating regulations for indoor air pollutant concentrations, especially in the public sector [38].

5. Q4. Are there thresholds for ventilation rates, and IAQ indicators that should be universally prescribed?

Building codes and standards specifying outdoor air ventilation rates in school buildings are primarily derived from human sensory ratings of air quality including odour intensity perceptions and evaluations of IAQ acceptability, performed immediately upon exposure (i.e. when entering a space) and mainly by adults (not schoolchildren) [119]. Using these data, most standards aim to prescribe ventilation rates to avoid dissatisfaction levels with IAQ greater than 20 %, which are predicted to occur at approximately 670 ppm CO_2 above the ambient outdoor level [120, 121] (Fig. 2).

Students are considered to be one of the major pollution sources in classrooms [122] (see Q3) therefore ventilation rates in schools are often designed to maintain CO_2 concentrations at a certain level, traditionally agreed to be below 1000 ppm [123], although other CO_2 exposure limits have also been recommended and used [124]. There are also normative ventilation provisions designed to account for other pollution sources, such as building materials and furnishings [91,125]. In deriving appropriate ventilation rates, it is typically assumed that the outdoor air is clean, which may frequently not to be the case [9,126] (see Q3). In mechanically ventilated spaces, appropriate particle filtration will remove particulates from the outdoors but not gaseous pollutants such as NO_2 or O_3. Gaseous pollutants should not be ignored however, since they are important determinants of health (especially for children) ([116]; WHO, 2021).

Indoor air quality classes, based on the mean CO_2 concentration, are described in the international standard ISO 16000–41 [117] in relation to the activity carried out in the room (Table 2). The use of fixed CO_2 thresholds, as an indicator of the outdoor air ventilation rate in classrooms is inherently uncertain [69]. Younger students are typically smaller than adults, so it is assumed that they emit less CO_2 [17] which may not be entirely true because of their typically higher activity levels, which increase their metabolic rate [120]. Consequently, classroom ventilation rates may be too low or inadequately ventilated if regulated according to a single fixed CO_2 concentration. Generally, classroom ventilation rates are found to be lower than in offices, and can be as low as 1–2 l/(s·person) and below [127] especially when airing is only achieved by intermittent window opening and the buildings are airtight.

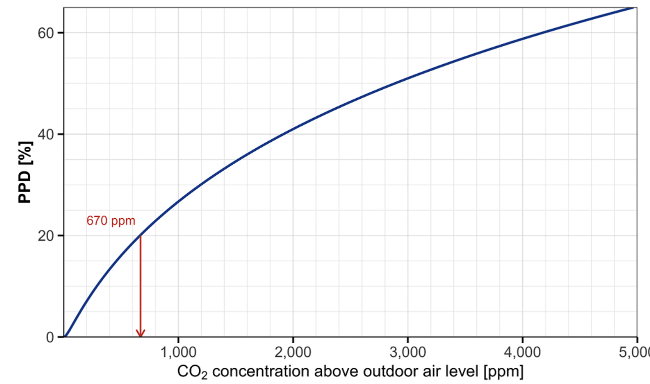

Fig. 2. Correlation between room CO_2 concentration (above outdoor level) and the percentage of persons dissatisfied (PPD), with the red arrow showing the 20% PPD CO_2 concentration, redrawn from Beinfait et al. [120] based on the work of Fanger [121]; where CO_2 (above outdoor level) is used as a proxy indicator for ventilation and bioeffluent emissions from human occupants.

Table 2
Indoor air quality classes for absolute CO_2 values (ISO 16000–41) [117].

Quality class	Description	Arithmetic mean of instantaneous CO_2 [ppm]*
A	Requirements for indoor rooms for the continuous stay of persons in which intellectual activities are carried out or which are used for regeneration	≤ 1000
B	General requirements for indoor rooms for the continuous stay of persons	>1000 ≤ 1400
C	Requirements for indoor rooms with brief use by persons	> 1400 ≤ 5000
Outside of class	Not acceptable for use by persons	> 5000

* **Note:** The quality class limits are defined as absolute indoor CO_2 ppm values ([117], p18). For measurements in school classrooms, the assessment period can be the duration of the lessons in an average day, but also in a single school hour. The sampling strategy of the room air, with regard to CO_2 measurement, shall be carried out in accordance with ISO 16000–26 [117].

The European Standard EN 16798–1 [125] prescribes outdoor air ventilation rates for classrooms between 4 and 12 l/(s·person)[3], depending on the targeted indoor environment class and the pollution category of the building (based on typical spatial densities of 2 m^2 per pupil). Whilst this standard has been widely adopted across Europe it is not legally enforceable, rather it is intended that EU member states use elements of such standards to improve their national building codes [128]. In order to interpret the guidance in EN 16798–1 it is necessary to define the category of indoor environmental quality (IEQ) appropriate to the level of expectation suitable for the occupants of the building (taking into account the level of pollution emitted by the building fabric[4]). According to EN 16798–1 "a normal level (of expectation) would be 'Medium',[5] whilst a 'High'[6] level may be selected for occupants with special needs (children, elderly, persons with disabilities, etc.)" [125], p18. Since schools are predominantly occupied by children, and some

[3] The ventilation rate should always be higher than 4 l/(s·person) (i.e. minimum 4 l/(s·person) for human emissions and an additional component for building and activity related emissions).

[4] Three polluting categories are typically considered, LPB-1 (very low-polluting), LPB-2 (low-polluting) and LPB-3 (non-low-polluting). Emissions criteria corresponding to these classes are defined in EN16798-1.

[5] Where 'Medium' corresponds to IEQ_{II}

[6] Where 'High' corresponds to IEQ_{I}

occupants will also have disabilities and special needs (including being in risk groups for asthma, long COVID etc.) the category IEQ_I (‘High’) would appear to be most appropriate for the safe and inclusive operation of classrooms [9].

ASHRAE Standard 62.1 has been adopted in many countries worldwide, its implementation is arguably more straightforward in that it prescribes outdoor air ventilation rates for educational facilities of 5 l/(s·person) plus 0.6 to 0.9 l/s per m^2 floor area, resulting in around 7 l/(s·person). In earlier versions of this standard from 1989 this rate was set to 8 l/(s·person). In addition, in the Standard 62.1 ventilation rates can also be determined using the so-called ‘indoor air quality procedure’ once the relevant pollutants have been identified; Addendum aa to ASHRAE Standard 62.1 [91] lists the chemical compounds commonly found in the indoor environment that should be considered. In the European standard EN16798–1, the lowest outdoor air ventilation rate is defined as 4 l/(s·person) in line with the HealthVent project that referred to this as ‘base rate’ ventilation [119]. This rate can only be used when the WHO air quality guidelines are satisfied, however it should be noted that it was established prior to the recent COVID-19 pandemic.

Guidance contained in the WHO “Roadmap to improve and ensure good indoor ventilation in the context of COVID-19” was developed during the emergency phase of the pandemic to help mitigate the spread of the SARS-CoV-2 virus globally [129]. During the emergency phase of the COVID-19 pandemic, ventilation guidelines for schools were discussed at length, and air change rates of up to 5 h^{-1} [130] and 6 h^{-1} [7] were recommended. ASHRAE Standard 241 – Control of Infectious Aerosols, is a voluntary global standard which was developed to establish minimum requirements for an infection risk management mode of operation (IRMM) in occupied buildings. The standard prescribes an ‘equivalent’ clean airflow rate (ECAi) for infection control in classrooms of 20 l/(s·person). The ventilation rates described above refer to so-called ‘fully mixed’ conditions, which, if not met, would require higher air flow rates [4,64]. Moving forward, classrooms must be prepared to deal with future infection waves and pandemics (see Q10), but it is also important to note that no ventilation rate or system can eliminate all health risks in schools [71] (see Q1, Q2 and Q5). A few studies have examined the effects of ventilation on short-term health-related absenteeism, and these are discussed in Q1; notably, reducing external and internal pollutant exposure reduces absence rates.

The recast Energy Performance of Buildings Directive (EPBD) [131], which entered into force in May 2024, introduced new provisions for IEQ in public buildings, which encompass both thermal comfort and ventilation/IAQ domains. One of the implications of this directive is that new school buildings must be equipped with measuring and control devices for monitoring and regulating IAQ and overall IEQ [132]. Member States will be required to transpose these new IEQ requirements into national legislation by 29 May 2026. Most European countries already provide guidance documents setting out the ventilation and IAQ requirements in schools, either through their building regulations or via supplementary guidance. For example in the UK Building Bulletin 101 (BB101) [133] provides guidelines for ventilation, thermal comfort, and indoor air quality in schools, which is widely used as a means to satisfy Approved Document F of The UK Building Regulations. Alongside this, The Department for Education has recently produced updated guidance on ventilation and air quality in education and childcare settings [134]. A drawback with devolved guidance and policies, even at the national level, is that they can result in inconsistencies in ventilation and IEQ/IAQ standards and practices [9,87]. Moreover, any such guidance needs to remain current, in relation to evolving knowledge, and have the capacity to respond to extraordinary situations (including epidemics and pandemics) (see Q10).

It is quite obvious that if health is to be prioritized, the existing WHO Guidelines [15] have to be met in all classrooms, which, besides sufficient ventilation, may imply particle filtration and gaseous air cleaning [9]. Once learning outcomes are considered, ventilation rates should ensure that CO_2 levels in classrooms remain below 900 ppm [23] a level which is in good agreement with the 800 ppm target for ‘health based’ ventilation, proposed for all public buildings [38,67] and is aligned with the conclusions of the review of ventilation-health relationships by Carrer et al., [20].

6. Q5. When are source control and/or additional air cleaning needed to reduce health risks?

Although ventilation is of primary importance both during normal school operations [23,31,86,135,] and during pandemics [38,73] the most effective way to ensure healthy indoor environments is to reduce, or preferably eliminate, the contaminant source (i.e. source control). This approach was proposed, amongst others, by the HealthVent project [119] and more than a century earlier by Pettenkofer [123].

There are numerous contaminant sources that influence IAQ and health in schools, such as dampness and mould [136], construction materials and furnishings [137]; consumables (for example glues, paints, and chalk dust [138]; the occupants (teachers and students) and their activities; but also contaminants originating outdoors can play an important role with respect to IAQ and health risks for teachers and students [8,139,140]. A reduction in contaminant concentrations due to a reduction in contaminant emissions directly results in an indoor environment with reduced exposure to certain types of pollutants. Source control should therefore be the primary means to improve IAQ, reducing the need for either high ventilation flow rates and/or additional air cleaning. Depending on the source however, source control may be more or less straightforward, (e.g. specifying low-emission materials is easier than reducing contaminants from human sources, such as exhaled pathogens).

In times of a pandemic or other high-risk events (in which human exhalation is the, potentially dangerous, source of contaminants) respirators or masks can be used to filter the inhaled air (exposure reduction) and the exhaled air (spread reduction, i.e. source control) [141–144]. Filtering face protection (FFP) reduces both the short- and long-range airborne transmission (see the definition provided in Q2) of pathogens from the infected person to other persons within the same room. This has been shown to be effective in reducing airborne infection risk when used properly [141,145–147], also in school settings [148–150]. However, masks have practical drawbacks, and some studies have reported no positive effects of simple mask use (e.g. [151]). This may be due to confounding factors, or for example due to inappropriate mask use [152] or the false reassurance (of complete protection) they may provide. In addition, it should be noted that relatively simple masks (e.g. fabric masks or even surgical masks) mainly influence the amount of exhaled aerosols entering the room but have less effect on the inhalation of aerosols. This is because of the reduced diameter of inhaled aerosols, due to evaporation, combined with the poor filtration efficiency of most simple face coverings in relation to smaller aerosols [142].

The use of respiratory grade masks (i.e. FFP2 or FFP3 grade) can provide significant additional protection [153] alongside ventilation and air cleaning, particularly in respect to short-range transmission, since transmission over short distances cannot be fully prevented by these processes [154] (see Q1). Ventilation and air cleaning normally act at the room level, and the flows resulting from room ventilation are generally not strong enough to create an aerodynamic barrier between two persons in close proximity. For this reason reducing the occupant density of a classroom, during a pandemic or epidemic, serves two distinct purposes: (i) by increasing the physical distance between individuals it reduces the risk of short-range transmission (ii) it directly reduces the emission rate of, potentially infectious, aerosols (i.e. source control).

Because higher airflow rates may not always be feasible due to capacity limitations, the ventilation system (if present) cannot always provide the target airflow rate needed for infection risk reduction (see

Q4). Additional use of air cleaning may then be a viable solution to dilute contaminant concentrations [38,45,47,155–157]. Air cleaning in classrooms, by filtration or other means, in the existing ventilation system or using stand-alone devices has been demonstrated to enhance IAQ by either filtering out particles [158–161] and/or gases [162] and/or deactivating pathogens in the air. Ultraviolet germicidal irradiation (UVGI) using upper-room UV-C light has also demonstrated significant potential to reduce airborne pathogens [47,163,164]. In this way the required amount of fresh supply air could be focused on fulfilling other IAQ criteria [157] thereby saving energy (reducing CO_2 emissions and economic costs) and avoiding significant investments in new ventilation systems.

It should be noted that air cleaning generally does not remove all gaseous contaminants from the air and should always be combined with adequate ventilation. Whilst using mobile air cleaners is generally considered a temporary solution in times of crisis, they can also be used as an interim solution to augment the clean air delivery rate (CADR) in existing naturally ventilated classrooms (see Q9). Differing conclusions on the performance of air cleaners in indoor environments (in terms of IAQ, operating costs, health, comfort and acceptability) can be found in the literature [38,45,165,166].

Source control, when combined with selective air cleaning (filtering, deactivation, etc.), in addition to ventilation, can be seen as part of an integrated approach to ensuring the optimal health of students and teachers whilst fostering a sustainable approach to the indoor environment [167].

7. Q6. Are natural ventilation strategies still viable, in terms of meeting emerging targets and standards?

Natural ventilation—where air enters and leaves buildings via naturally occurring forces of buoyancy and/or wind—offers multiple benefits when carefully designed and controlled. These advantages include reduced maintenance requirements, lower pollution risk from air bypassing ducts and filters, passive cooling capabilities, and decreased operating costs compared to mechanical alternatives.

School ventilation standards across Europe reflect a complex interplay between IEQ (encompassing IAQ, acoustics, lighting, and thermal comfort) and energy considerations. At the European level, the European Committee for Standardization (CEN) provides the foundational standard EN 16798–1:2019 [125] (see Q4). Compliance with the ‘High’ category (IEQ_I) (10 l/(s·person)) can be considered an appropriate baseline outdoor air ventilation rate for most school buildings, provided that acceptable room temperatures and relative humidity levels are duly maintained.

While natural ventilation can potentially reduce energy costs by eliminating energy required for fans and supplementary cooling, it increasingly struggles to meet stringent energy efficiency standards for winter heating without supplementary systems, such as mechanical ventilation with heat recovery [3]. This challenge becomes particularly pronounced in colder European climates and in densely occupied buildings (such as schools) where heat loss through ventilation constitutes a significant energy consideration.

Natural ventilation strategies in European schools have been extensively studied, with research revealing both opportunities and challenges in meeting modern standards. Evidence suggests that while natural ventilation should always be incorporated in school design (as a means of purging excess heat or in case of mechanical failure), it is likely to be insufficient in maintaining comfortable conditions under projected climate change scenarios. Hybrid (or mixed mode) ventilation systems will increasingly become necessary, highlighting the need for holistic approaches to ventilation design in educational facilities [3,9].

A significant proportion of Mediterranean schools rely on natural ventilation [168], and this remains feasible when outdoor air quality and noise levels permit [169]. In cooling dominated Southern European climates such implementations require careful attention to building orientation, solar protection, thermal mass utilization, night cooling strategies, openable window positioning, and maximising opportunities for purge ventilation (via natural or hybrid (i.e. fan assisted) means) during unoccupied periods. When thoughtfully combined, these fundamental elements create effective natural (and mixed-mode) ventilation systems.

Significant disadvantages of natural ventilation include compromised supply air quality in polluted outdoor environments, where filtration presents substantial challenges. This limitation has become particularly critical in light of tightened ambient air pollution thresholds (see Q3, Fig. 1 and Table 1) [15,170]. Additional concerns include increased draught risks in scenarios requiring high ventilation rates during colder months and disturbances from external noise sources [9]. Background noise is a particular issue in many urban classrooms in Europe, with several studies reporting façade noise levels frequently exceeding 50 dBA [171,172]. Detailed guidance on acceptable noise levels in schools is available in most countries, where an upper limit for indoor ambient noise (LAeq, 30mins) of around 35 dB is typically considered appropriate for new build classrooms [173]. Careful assessment of background noise, on each façade, during the planning stage is an essential pre-requisite when natural ventilation is being considered as the primary ventilation strategy.

Despite these challenges, natural ventilation is still regarded as an important design consideration in school buildings across many European regions, when used as part of a mixed-mode solution or as a back-up to mechanical systems. In considering whether natural ventilation is appropriate, as part of new school design, it is important to distinguish between design-optimised natural ventilation versus traditional operator-dependent window opening. The successful implementation of natural ventilation, in modern schools, relies on the smart integration of sophisticated control strategies, particularly in urban areas and regions experiencing more extreme weather events due to climate change.

Effective control strategies should combine temperature, air quality and CO_2-based monitoring systems [174] that are readily understandable by occupants (see Q7). These systems must offer users meaningful, logical intervention options to improve local comfort, such as easily operable windows or adjustable ceiling fan speeds. Too frequently, user-controlled windows and dampers require impractical actions—climbing on furniture or exerting significant force—resulting in abandonment of these features or risk of injury.

Schools considering natural ventilation strategies today must adopt a comprehensive approach to planning and implementation. This process begins with detailed site-specific feasibility studies examining prevailing wind patterns, outdoor pollution levels (see Q3) and façade level noise, as well as future temperature projections to understand local conditions and constraints. These studies should inform meaningful dialogue with building owners, planners and building control, to establish agreed-upon performance standards.

This conceptual design work should guide the implementation of design-optimised natural ventilation, which implies the use of hybrid (mechanical and/or room based filtration) systems capable of supplementing natural ventilation when needed. Such systems typical require smart controls capable of optimizing ventilation, based on occupancy patterns and environmental conditions. Future climate scenarios must be carefully considered during the design phase to ensure the long-term viability of chosen solutions.

Successful implementation requires clients who are knowledgeable about IAQ, thermal comfort, and available options (like night cooling and weekend purging). This knowledge transfer depends on professional institutions and government departments issuing appropriate guidance to building managers and users, that relates environmental performance to measurable factors such as temperature, IAQ, and CO_2 levels. An accessible checklist helping determine potential future mechanical cooling needs would significantly assist planning and implementation.

The in-use performance of these systems depends heavily on meticulous commissioning practices and ongoing monitoring of

Table 3
Impact of different filter grades and partial fouling on fan power. (Figures based on one ventilation unit at 8 l/(s·person), 16 occupants. Two units per classroom with occupancy of 32).

Filter grade[1]	Clean dP [Pa]	Dirty dP [Pa]	Increase in SFP at 475 m^3/h (assuming partially dirty filters) [W/l·s]	Resulting increase in fan power for 2 units at 475 m^3/h [W]
Coarse 30 %	15~20	~25	<0.1	15
Coarse 60 %	40~60	~200	~0.3	80
ePM_1 50 %	60~100	~300	~0.45	120

environmental performance factors (including thermal comfort, IAQ, and ventilation system operation). Such monitoring plays a crucial role in identifying and resolving unexpected issues, ensuring systems perform as intended. Involving building users in monitoring activities has proven effective, as demonstrated by Geelen et al., [175] and McLeod et al. [9], who successfully tested the use of CO_2 warning devices, paired with educational packages, in naturally ventilated school environments.

8. Q7: What is the role of building design and occupant behaviour in achieving a good IAQ?

It is important to remember that 'infectious' aerosols are not the only possible pollutants present in a space. Think of emissions from construction and furnishing materials, the outdoor air, pollutants originating from poor maintenance of ventilation systems, and not forgetting all those VOCs and particles that are released during the many activities occupants perform [176]. This necessitates dealing with a complex mix of pollutants which can change over time. Those pollutants can interact with each other, as well as with other materials and pollution sources (including via ad/de-sorption) and these processes are also influenced by ventilation, both mechanical and natural.

Interactions with the environment can cause additional unwanted effects or even interfere with the primary effect. For example, increasing ventilation by opening a window can introduce outdoor pollutants, cold air during wintertime, and warm air in the summer. During the early stages of the COVID-19 pandemic, windows and doors in schools were open almost constantly, even in the presence of mechanical ventilation [177]. Consequently, many school children were sitting with their coats on in the classroom, fighting the cold air from outdoors. In addition to cold air, opening windows can introduce unwanted noise from outdoors (see Q6). Equally, mechanical ventilation systems and mobile air cleaning devices, which were introduced to clean the air from infectious aerosols, can give rise to problems with internal noise as well as causing unwanted draughts [45,165].

The heating, cooling, and ventilation (HVAC) of a classroom is an interplay between solar radiation coming in, the HVAC systems present, solar shading devices (sometimes hampering ventilation), operable windows, and the actions of the teachers and students (e.g. opening doors, windows, and using heating and ventilation devices, etc.) [178]. Moreover, whilst a certain action by a teacher can improve the conditions for one child, for another child the same action can cause a problem [179], because children have different preferences and needs [180].

The interaction between school building design and occupant behaviour (e.g. activities such as painting, physical exercise, and cleaning) creates a mix of stressors over time, resulting in (combined) effects on occupants with different preferences and needs. Moreover, the possible consequences of climate change for indoor environments (e.g. heatwaves, increase in smog frequency, etc.) need to be considered [181] (see Q10). For ventilation this entails that the new generation of ventilation systems should be fully integrated into the building design process and not just used to address the general ventilation of a classroom (in relation to delivering good IAQ). Rather, they need to provide a range of ventilation options, that fulfil the demands of the occupants over time, whether related to health or comfort. Moreover, the overarching aim should be to strive not only for good IAQ but for good IEQ. This requires an integrated approach accounting for all stressors (i.e. physical and psychosocial; positive and negative) [182] and other building- and occupant-related indicators [183]. Indicators that go well beyond the current comfort-based dose-related metrics (e.g. CO_2, air temperature, etc.) commonly used to control and assess IEQ [184].

9. Q8: Are the energetic, environmental, and cost implications of mechanical ventilation justifiable?

In most European school classrooms it is difficult to meet current standards (such as EN 16798 and ISO 16000–41) which recommend average CO_2 values at or below 1000 ppm during lessons, and almost impossible to achieve these targets in winter without the use of mechanical ventilation while maintaining acceptable thermal comfort [9,185]. Furthermore, in many locations in Europe the outside air quality exceeds the WHO guidelines levels for pollutants such as $PM_{2.5}$, PM_{10}, NO_2, and ozone (O_3) (Fig. 1), with some locations having mean values above thresholds which should not be breached more than 3 times per year [9,170,186]. If outside air quality or noise makes natural ventilation via windows undesirable, mechanical ventilation systems offer the potential to filter or treat all incoming air as required.

Mechanical Ventilation with Heat Recovery (MVHR) saves operational energy in a heating-dominated climate (i.e. most of central and northern Europe) and it will save more the colder the climate is. In cooling-dominated Mediterranean climates, MVHR generally delivers smaller energy savings than in heating-dominated regions, and its feasibility depends on the specific climate characteristics and system design. Enthalpy recovery and effective summer bypass systems can improve performance in hot-humid conditions, whereas in hot-dry climates, simpler ventilation strategies may offer comparable benefits at lower cost. However, at certain times of the year (when the outside air temperature approaches the internal set point temperature), an MVHR system will consume more energy than it saves. This occurs whenever the fan energy use exceeds the useful heat (or coolth) recovered. For example, at outside temperatures above 16 °C, heat recovery is rarely required for energetic purposes, and fan energy use must be minimised by bypassing the heat exchanger [187,188]. Alternatively, the system must be turned off to revert to natural ventilation. In addition, classrooms have relatively high internal heat gains (due to their high occupancy levels). Maximising heat recovery during periods of full occupancy may therefore not be the optimum approach to energy efficiency.

Very high efficiency heat exchangers have high levels of pressure drop due to the narrow plate spacing. They also require relatively high grades of filtration upstream of the exchanger to minimise fouling. An example of the impact of differing grades of filtration on fan power is shown in Table 3. For significant periods of the year, the additional fan power required to overcome the high-pressure drops (in both the heat exchanger and the filters) is either unnecessary or will exceed the heat recovered. Significantly reducing the heat exchanger efficiency (e.g. to around 50 %) will reduce the heat exchanger pressure drop massively.[7] This means that only insect level filtration would be required, to protect the heat exchanger, (i.e., ISO coarse 30 % (ISO, 2016), or G2 [189][8]). This can have a direct positive impact on the overall annual energy use and reduces maintenance costs (due to cheaper filters and less frequent replacement/cleaning). In cases where higher grade filtration is required, the use of low-pressure heat exchangers will help to reduce the total fan power required.

The costs associated with purchasing and installing mechanical ventilation systems in buildings encompass several dimensions, including initial capital investment, ongoing operational and maintenance costs, and potential modifications to existing structures. When viewed solely as having a financial implication for the building owner, the societal impacts are totally ignored. In a US study of California schools, it was shown that the societal benefits far outweighed the operating costs [86]. By using mechanical ventilation the schools recorded a decrease in absenteeism by 3.4 %, which in turn increased the governmental funding for attendance by $33 million (USD) annually, whilst at the same time only increasing the operation costs by $4 million (USD). Based on a review of the literature Fisk [139] argued that the net annual costs of increasing ventilation rates in US schools would amount to less than 0.1 % of typical public spending on elementary and secondary education.

Research investigating this issue in the European context is sparse, however a study by Wargocki et al., [190] investigated the socio-economic effects of upgrading the IAQ in Danish schools to the level of Swedish schools. The results showed that improved air quality in Danish schools could result in an increase in the Gross Domestic Product (GDP) of €173 million per annum, and in the public finances of €37 million per annum (based on 2014 figures). Similar cost/benefit studies are needed to account for diverse European economic contexts, and this is the subject of ongoing research. If such research consistently demonstrates a net positive financial impact it would allow governments to justify extensive remedial works. Ultimately, the funding of better IAQ in schools is a political decision and one which is likely to require financial justification. This opens up the question of how the health and learning benefits of improved ventilation and IEQ/IAQ can be optimised at a societal level if adequate governmental or EU funding is forthcoming.

Mechanical ventilation offers the potential to provide good IAQ and thermal comfort, but to optimise annual energy efficiency, the instantaneous heating and cooling loads must be fully assessed. An analysis of the relationship between total HVAC related energy use and ventilation rates in European buildings, in three different climatic contexts, is provided by Santos and Leal, [191]. However, the true benefit of such systems only becomes evident when the system design is optimised, and the wider health and societal impacts are included in the decision-making process [192].

As Europe moves to a decarbonised electricty grid, the environmental impact of operating mechanical ventilation systems will decrease, but so too will the potential carbon savings. Countries like Finland, Norway, Lithuania, and Sweden have a very low grid carbon intensity (meaning they rely heavily on clean energy resources, such as solar, wind, nuclear and hydroelectric power). In Norway, greenhouse gas emissions from building services, including HVAC systems, are estimated to contribute 20–40 % of the total material emissions in new building constructions, with this figure rising to 80 % in refurbishment projects [193]. More specifically, in the context of a Norwegian office building, Liu et al., [194] found that the impact of embodied carbon emissions exceeds that of operational emissions in ventilation ductwork when the emission intensity of electricity generation falls below 0.14 kg CO_2/kWh.

Under a fully decarbonised European energy system, operational carbon emissions from buildings could approach near-zero levels by 2050; however, this outcome is contingent on factors such as electricity grid decarbonisation, widespread electrification (e.g. heat pumps), and sufficient on-site or grid-supplied renewable generation (e.g. PV and storage) to meet building energy demand [195]. As a result, the relative importance of operational carbon diminishes under such scenarios, while embodied carbon, service life and maintenance requirements will increasingly dominate the whole-life environmental impacts [3].

10. Q9. What are the barriers and constraints to retrofitting mechanical ventilation and air-cleaning devices in classrooms?

Many European classrooms need substantial improvement in their IAQ. To a significant extent, this can be achieved by installing mechanical ventilation and, where needed, air-cleaning devices. However, this task is met with numerous barriers and constraints. To tackle this challenge, it is helpful to distinguish between the organisation of the project (i.e. the process) and the technical solutions.

10.1. Building & design process

Process-related barriers and constraints include limited awareness of the importance of indoor climate by decision makers, a lack of quality assurance, and the huge scale of the work.

One should be aware that when (re)designing educational buildings aspects like IEQ are often not prioritised by decision makers. A Swedish study [196] found, for example, that issues such as the maintenance level, energy demand, and the indoor environment in school buildings were not really addressed during design sessions, not even by representatives of the school board or teachers. School design criteria tend to emphasise aspects like accessibility, functionality (with respect to teaching requirements) in addition to architectural qualities.

When starting a project, decision makers should define the desired quality level for ventilation and IAQ alongside the wider environmental quality and energy performance aspects (see Q4). Key questions include: what is the ambition of the school board or local government for its new buildings? Can this ambition be realized within existing buildings? Additionally, achieving the desired quality requires verification, in order to avoid performance gaps. Tools are needed to (i) set ambitions, (ii) quantify the baseline situation, (iii) establish design targets, and (iv) test if design targets are met. In the Netherlands, the Programme of Requirements “Frisse Scholen” has been used since 2008 [197], which includes requirements on IAQ, thermal comfort, light, acoustics and energy at three quality levels. Also REHVA Guidebook No. 13 [198] provides guidance on the indoor environment and energy efficiency in educational buildings whilst VDI 6022 [199] addresses hygiene requirements for the design and operation of effective heating, ventilation, and air-conditioning (HVAC) systems. CIBSE Guide TM57 Integrated school design [200] adopts a similar approach, and identifies that issues relating to design, building operation, handover procedures, and the complexity of building management systems have been found to have the most significant impact on outcomes.

Finally, the number of schools needing improvement, across Europe, is enormous, making it impossible to retrofit all school buildings simultaneously. A phased approach is therefore necessary, and this requires triaging the existing building stock in order to prioritise the worst affected schools. This process should be based on current ventilation rates, as well as IAQ and IEQ, but also considering impending maintenance requirements and energy consumption.

[7] A reduction in the heat exchanger efficiency from using a counter flow exchanger (at 80% efficiency) to a cross flow (at 50% efficiency) will result in excess of a 75% reduction in the pressure drop.

[8] The terms “ISO coarse 30%” or “G2” refer to filter classifications — specifically, how effective an air filter is at capturing coarse (larger) particles (ISO 16890). Where 30% means the filter removes about 30% of coarse dust particles in standardised testing. G2 is the previous DIN EN 779:2012 classification, which ISO 16890 (2016) has now replaced.

10.2. Technical solutions

The main barriers in delivering technical solutions to improve air quality in schools are limited budgets, along with the need for specific tailored solutions for schools given the local environmental context.

Schools differ from other building types due to their high occupancy rates, necessitating the delivery of large volumes of air, compared to buildings like offices. This makes noise control (noise from the ventilation system and/or traffic noise from outside in the case of natural ventilation) and draught prevention significant challenges.

Solutions must, of course, be robust and energy efficient (see Q8). Moreover, maintainability and usability are important considerations in designing systems that are reliable and perform well under both normal and 'non-standard' conditions (see Q10). These are critical aspects where ventilation systems for schools often underperform. The frequency, ease, and cost of maintenance should be addressed in the design phase to make sure that— in real life—systems perform as intended and remain operational. The same applies to the usability of the system; where personal control at room level is beneficial to user satisfaction [201] and building management systems are more valuable if they provide long-term IEQ data (e.g. CO_2 concentrations and temperatures) in order to verify performance throughout the seasons.

Nevertheless, there are various ventilation concepts that have proven to be robust and that ensure a healthy and comfortable indoor climate in classrooms. These include central and decentralized systems, mixing ventilation systems with wall grills, ceiling diffusers, or textile ducts, and displacement ventilation with air supply from the floor or wall. In addition, local and/or personal solutions could be considered (personal ventilation, local air cleaning, etc.) according to the rooms intended usage and the environmental context. Even in existing school buildings, with natural ventilation by manually operated windows, ventilation rates can be improved by low-cost interventions like the introduction of visual alerting (e.g. red, amber, and green (RAG)) CO_2 sensors [9,175]. The suitability of a particular system depends on the specific context of the school (including the local climate, building design (e.g. ceiling heights, basement space), urban context (e.g. traffic noise, air pollution), as well as funding availability).

Since the COVID-19 pandemic began, there has been increased attention on using air-cleaning devices to improve air quality in classrooms and reduce the transmission of infectious diseases [47] (See Q5). When properly specified (e.g., no ozone production, high CADR, low fan-noise), these devices can enhance air quality both during periods of elevated infectious disease transmission, as well as under normal operating conditions. However, their practical integration into classrooms can be challenging; they can't be placed in the middle of the room and cannot produce draughts or emit significant noise. Therefore, suppliers and designers must develop solutions tailored for schools to make air-cleaning devices a viable adjunct to ventilation.

10.2.1. Implementation

Addressing the enormous task of improving classroom IAQ and ventilation, whilst avoiding performance gaps, requires a multifaceted approach that balances the conflicting challenges and constraints. As Balvers et al., [202] concluded for ventilation in dwellings, the success of mechanical ventilation systems depends on properly specified design requirements, quality assurance, inspection, enforcement of building codes, adequate budgets, and coordination among the design and construction team. These principles are equally applicable to schools, ensuring that retrofitting efforts lead to significant improvements in IAQ, learning performance and health. Installation and maintenance costs associated with new ventilation systems are often prohibitive for cash-strapped public schools and this is where nationally coordinated funding (see Q8), and support will be needed to avoid the risk of exacerbating existing health and educational inequalities [9]. Performance monitoring is an essential, but often overlooked aspect of successful implementation; a recent paper proposed the schoolTAIL rating scheme as an effective means to identify potential problems and prioritise IEQ and IAQ remediations in schools [203].

11. Q10 What implications do climate change and emerging risks have for ventilation in European schools?

Climate change presents complex challenges for public health and the safe operation of schools. Studies indicate that as mean air temperatures rise and precipitation patterns shift, Europe will experience an increase in both the amplitude and duration of heatwaves. As a direct consequence of this, the potential for wildfires is also exacerbated, particularly when global average surface temperatures exceed 1.5 °C above pre-industrial levels [204], a point which was recently surpassed [205]. Moreover, climatic changes are enabling existing tropical diseases (such as Lassa fever) to extend their reach far beyond their original origins, whilst emergent zoonotic diseases and novel viral pandemics are predicted to become far more frequent [206,207]. Consequently, the lessons learned from the COVID-19 pandemic, previous heat waves and wildfires must inform ventilation strategies to ensure that schools are better prepared to face such eventualities in the future.

Whilst the COVID-19 pandemic temporarily heightened teachers' and students' understanding of the importance of increasing ventilation rates [65], events such as overheating and wildfires significantly influence ventilation behaviour in buildings in a negative way. This is primarily due to the adverse effects of smoke and air pollution on IAQ [208, 209]. The infiltration of outdoor pollutants, particularly fine particulate matter ($PM_{2.5}$), into indoor spaces is a critical concern. Studies have shown that natural ventilation rates can significantly affect IAQ, with closed windows leading to higher concentrations of indoor pollutants in some cases [174] and lower levels in others [116], depending on the source of the pollutants.

The behaviour of teachers and students in classrooms, including their willingness to open windows for ventilation, is dominated by factors such as temperature and noise [9], leading to a reluctance to open windows in summer during prolonged periods of very hot weather. Some research also shows that window-opening behaviour can be influenced by the perceived risk of outdoor air quality, which can conversely lead to increased exposure to toxic indoor substances [174, 210].

The presence of mechanical ventilation with air filtration systems (such as HEPA and activated carbon filters) has been shown to improve IAQ significantly during pandemics [65] and wildfire events [211,212], yet their effectiveness is equally contingent upon proper usage and maintenance [213]. Often caretakers, with little or no training or guidance, are responsible for the operation and maintenance of complex mechanical systems. While these systems can help mitigate indoor air pollution, their performance is often compromised when they are not utilized correctly (e.g. irregular maintenance, flow-rate balancing, air filter changes) or when schools simply turn them off, and rely solely on natural ventilation, due to the running costs [9,214].

The longterm robustness of any ventilation strategy is highly dependent on future climate scenarios, such as increased temperatures, extreme weather events, outside pollution and future pandemics [215–217]. Flexibility and spare capacity play a key role in achieving resilient system design [218], for example mixed-mode ventilation systems, which augment functional natural ventilation systems with mechanical ventilation [219], are likely to be more effective in managing overheating and improving IAQ in schools, particularly in regions facing climate change challenges [220–222]. Climate change and emerging risks pose significant challenges for ventilation in European schools, underscoring the need for smart control strategies that harness AI—for example, predicting overheating and activating night purge ventilation or pre-conditioning—and optimally leveraging big data sources, such as wastewater monitoring or future real-time pathogen sensing, both to inform system control and to provide meaningful feedback to occupants [223].

In addition to the above, the sociotechnical aspects of ventilation play a critical role in their acceptance and effectiveness. Building design and management practices in schools must evolve to foster a holistic approach that integrates technological solutions with user behaviour. This includes critically evaluating the positioning and gearing of window openings in relation to draughts and the ability to trim windows effectively under different environmental conditions. Training teachers and students to understand and utilise natural ventilation more effectively, as well as implementing smart ventilation system controls, that can adapt to real-time occupancy and environmental changes, are equally important. The integration of feedback mechanisms and sensor technology (including CO_2 and common particulate and gaseous pollutants) [224] can enhance the ability of ventilation systems and room occupants to adapt appropriately to varying environmental conditions.

12. Conclusions

Despite some remaining uncertainties regarding the nature of causality, current research supports the immediate implementation of evidence-based ventilation strategies in European schools. Targeted outdoor air ventilation rates compliant with the highest category of European Norm EN 16798–1:2019 (i.e. circa 10 l/(s·person), depending on background pollution from the building) should be considered an appropriate baseline for new classrooms. This outdoor air ventilation rate will, in most school settings, ensure that a steady-state absolute CO_2 concentration of 900 ppm is not exceeded. A body of evidence shows that the provision of clean outdoor air at these rates will reduce the concentration of airborne pathogens and minimise the disruption to learning in schools. While these values may require future refinement or augmentation (for example in response to novel airborne pandemics or seasonal outbreaks), and as further data become available, delaying action is no longer justified.

For existing buildings, a lower baseline ventilation rate[9] might be temporarily acceptable when investments in improvement measures are not immediately feasible, or when the envisaged ventilation solutions cannot be integrated within the current building structure. In such cases, alternative measures (such as portable air cleaning devices, and CO_2 monitoring) should be instigated to improve the clean air delivery rate to an acceptable level. However, the overarching aim should always be to achieve the outdoor air ventilation rates recommended for new school buildings.

Given the widespread non-compliance with existing standards, the authors of this paper are united in their view that the current situation should be immediately overhauled. These guidelines can be readily implemented using e.g. room-based CO_2 monitoring, provided that adequate ventilation (with clean outdoor air) is possible and space conditioning systems are in place. Increased airflow rates alone are insufficient to address the full range of indoor air and environmental quality challenges facing schools however, which is why monitored IAQ and IEQ parameters should be made visible to room users. Similarly, such data should be logged in building automation and control systems for performance assessment and maintenance support purposes. Multi-layered strategies that integrate source control, mechanical filtration, air-cleaning, upper-room UV-C disinfection, and low-energy cooling (when required), in response to real-time data, can provide greater resilience and adaptability than reliance solely on dilution approaches to ventilation.

The revised Energy Performance of Buildings Directive (EPBD), in 2024, [131] heralded a paradigm shift in European construction, elevating IEQ from a comfort consideration to a regulatory requirement. One of the implications of this directive is that new school buildings must now be equipped with measuring and control devices for monitoring and regulating IAQ and overall IEQ, in order to maintain a healthy indoor climate. In most new European schools these changes will imply the installation of decentralised mechanical ventilation systems, in order to maintain acceptable levels of indoor environmental quality year-round. Additional monitoring of NO_2, O_3, VOCs, PM2.5, and PM10, alongside common indoor environmental quality parameters (such as temperature and relative humidity) is strongly recommended to ensure compliance with best practice and existing EU and WHO air quality guidelines.

Continuous research and field validation will allow these recommendations to be updated and optimized over time and will encourage the standardised monitoring and reporting of indoor air quality in schools.

The authors envisage a future characterised by responsive ventilation and air-cleaning systems, informed by intelligent controls, which utilise a growing spectrum of environmental data. Such systems must also encompass occupant feedback and over-rides (including the possibility to ventilate naturally via openable windows); in order to provide optimal learning environments, even under more extreme future climatic scenarios. Delivering such a vision requires policy harmonisation at the European level, with enforceable legislation and funding prioritisation, to ensure that no school is left behind.

CRediT authorship contribution statement

Robert S. McLeod: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Ulla Haverinen-Shaughnessy:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition. **Pawel Wargocki:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Marcel Loomans:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Tunga Salthammer:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation. **Twan van Hooff:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Malcolm J. Cook:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Philomena M. Bluyssen:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Atze Boerstra:** Visualization, Validation, Methodology, Investigation. **Froukje van Dijken:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Michael Swainson:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Christina J. Hopfe:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition.

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.

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[9] The lowest baseline outdoor air ventilation rate should not be less than 4 l/(s·person) with an additional allowance for emissions from the building fabric (see Q4) corresponding to a steady state absolute CO_2 concentration of around 1600 ppm. Whilst a higher ventilation rate would always be recommended.

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Data availability

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

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