Journal of Building Engineering 57 (2022) 104908

Contents lists available at ScienceDirect

Journal of Building Engineering

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

Indoor air quality and health in schools: A critical review for developing the roadmap for the future school environment

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ARTICLE INFO

Keywords:
Classroom air quality
Ventilation
Exposure risk
Energy use in schools
Particle matter
Volatile organic compounds

ABSTRACT

Several research studies have ranked indoor pollution among the top environmental risks to public health in recent years. Good indoor air quality is an essential component of a healthy indoor environment and significantly affects human health and well-being. Poor air quality in such environments may cause respiratory disease for millions of pupils around the globe and, in the current pandemic-dominated era, require ever more urgent actions to tackle the burden of its impacts.

The poor indoor quality in such environments could result from poor management, operation, maintenance, and cleaning. Pupils are a different segment of the population from adults in many ways, and they are more exposed to the poor indoor environment: They breathe in more air per unit weight and are more sensitive to heat/cold and moisture. Thus, their vulnerability is higher than adults, and poor conditions may affect proper development.

However, a healthy learning environment can reduce the absence rate, improves test scores, and enhances pupil/teacher learning/teaching productivity. In this article, we analyzed recent literature on indoor air quality and health in schools, with the primary focus on ventilation, thermal comfort, productivity, and exposure risk. This study conducts a comprehensive review to summarizes the existing knowledge to highlight the latest research and solutions and proposes a roadmap for the future school environment. In conclusion, we summarize the critical limitations

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https://doi.org/10.1016/j.jobe.2022.104908
Received 4 March 2022; Received in revised form 6 June 2022; Accepted 30 June 2022
Available online 8 July 2022
2352-7102/

of the existing studies, reveal insights for future research directions, and propose a roadmap for further improvements in school air quality. More parameters and specific data should be obtained from in-site measurements to get a more in-depth understanding at contaminant characteristics. Meanwhile, site-specific strategies for different school locations, such as proximity to transportation routes and industrial areas, should be developed to suit the characteristics of schools in different regions. The socio-economic consequences of health and performance effects on children in classrooms should be considered. There is a great need for more comprehensive studies with larger sample sizes to study on environmental health exposure, student performance, and indoor satisfaction. More complex mitigation measures should be evaluated by considering energy efficiency, IAQ and health effects.

Abbreviation list

AI	Artificial intelligence
CAQ	Classroom air quality
CAV	Constant air volume
CFD	Computational fluid dynamics
CFU	Colony-forming units
CR	Cancer risk
DCV	Demand controlled ventilation
DREAM	Danish Rational Economic Agency Model
DV	Displacement Ventilation
EPA	Environmental Protection Agency
EUI	Energy Use Intensity
GDP	Gross domestic product
HI	Hazard index
HQ	Hazard quotient
HVAC	Heating, ventilation, and air conditioning
I/O	Indoor/Outdoor (Time spend inside versus the outside)
IAQ	Indoor air quality
ICT	Information and Communications Technology
IoT	Internet of things
MV	Mixing ventilation
PM	Particle matter
NATA	National Air Toxics Assessment
PV	Personalized ventilation
TVOC	Total volatile organic compounds
VAV	Variable air volume
VOC	Volatile organic compounds
WHO	World health organization

1. Introduction

The primary purpose of a school is to provide children with the optimal environment for their learning and development. Schools have always been a second home for the pupils, and they spend most of their time indoors while at school (almost 12% of their time inside classrooms) [1–4]. Schools are among the critical social infrastructures in society and are often the focus for children's social activity. Classrooms are more congested than other workplaces, with an occupancy density of approximately four times that of office buildings [5]. Good indoor air quality (IAQ) in classrooms is essential because it may affect the health, performance, alertness, ability to concentrate, and comfort of pupils and teachers. Classrooms have typically been justified as an important built environment type by reference to the adverse effects of unfavorable indoor conditions on pupils' health, comfort, and academic performance [2]. Children are sensitive to various environmental exposures during this developmental stage of their life, which can have long-term negative consequences such as respiratory disease and low cognitive function [6]. In addition, the risk of cross-contamination in classrooms is usually higher than in other indoor environments and poses logistical challenges and/or risks of transmission.

Studies have shown that the conditions in schools are inadequate and often significantly worse than in offices and dwellings [7–9]. These conditions are known to reduce comfort and can also cause health problems [8,10–12]. This is particularly unfortunate as children of school age are vulnerable, and their bodies are still growing [13–15]. Poor conditions in schools also impact learning progression [16,17]. This is particularly important as it may affect the children's future quality of life with economic implications for society [18,19]. All conditions that shape indoor environmental quality in classrooms influence children's learning progression and cognitive performance. Pupil's performance are affected by many parameters, such as classroom temperature, air quality, lighting, and acoustics [20,21].

The school ventilation system is a primary tool for ensuring a safe, comfortable, and healthy indoor environment. Thermal comfort levels and acceptable IAQ are crucial in producing an environment that promotes optimal educational and health outcomes [22–24]. Previous research studies in school environments have revealed inadequate and often poor classroom air quality (CAQ), causing an increased risk for respiratory illnesses and other health-related symptoms [25–27]. Researchers reported diverse CAQ levels in school buildings in different parts of the world depending on climate conditions, outdoor pollution levels, occupancy rates, activity levels, ventilation types and their corresponding flow rate, and also building practices [28,29].

The CAQ depends on several factors, including the sources of indoor and outdoor pollution, dilution, and removal of pollutants by ventilation [30–32]. The type of ventilation system and air distribution within the classroom will also affect air quality.

Research to date that examined the effects of CAQ on children's cognitive performance and learning has addressed the factors that impact indoor air quality and emphasized outdoor air ventilation rates as the CAQ indicator [17]. The reason is that there are no agreed indexes of indoor air quality and ventilation rate is associated with contaminant exposure levels [20,33]. Often, carbon dioxide (CO_2) concentration is used [34] as the marker of ventilation adequacy in the presence of occupants [35] because, treated as a tracer gas, it is related to the ventilation rate per person. Research has shown that the level of CO_2 in classrooms can increase to very high levels due to inadequate ventilation rates [36,37]. It is generally assumed that the higher the CO_2 concentration, the poorer the air quality (less dilution). Although CO_2 has frequently been used to characterize air quality in classrooms, some research has focused on specific pollutants such as particulate matter or contaminants with outdoor sources [38–41].

In this article, we summarize and explore the most relevant and recent research studies that have been conducted on school IAQ and related social and health impacts on pupils and staff. We also critically reflect on the existing knowledge and literature whilst highlighting the areas with the highest uncertainties. Our focus is on identifying how different factors affect CAQ and comfort in schools, and hence pupils' health and wellbeing. Based on this review of the literature, we have also proposed a roadmap to improve indoor air quality in schools.

2. Methodology

2.1. Data inclusion, extraction, and analysis

This section presents the research methodology and brief statistical analysis on the reviewed articles to understand the current research trends. This review is formulated based on peer-reviewed journal articles from several renowned academic databases, such as Web of Science, Scopus, Science Direct, and SAGE journals. The fundamental purpose of critically review the most recent links between CAQ and the cognitive skills and abilities of pupils along with the consequences for progressive learning, to highlight research gaps, and to propose recommendations for further research. In this review, peer-reviewed journals across the world were considered. A few conference papers, thesis, standards, and technical guidelines were also analyzed to enhance the quality of the review.

Students' perceptions of the indoor environmental quality are affected by multiple parameters [42]. Among all these parameters, thermal comfort and IAQ are the key factors that significantly affect students' feelings of the indoor environments [43,44]. Moreover, the IAQ also interacts with thermal comfort through varied occupant sensations [44]. The sources of indoor and outdoor pollution, dilution, and removal of pollutants by ventilation are the key factors in determining IAQ [30–32]. The type of ventilation system and air distribution within the classroom will also affect air quality.

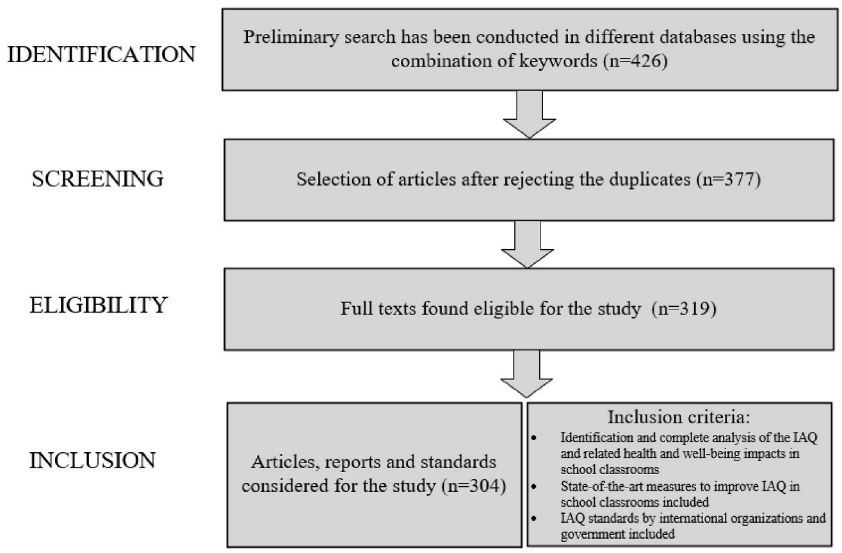

Fig. 1. Flow chart of the procedure followed for the inclusion of research articles.

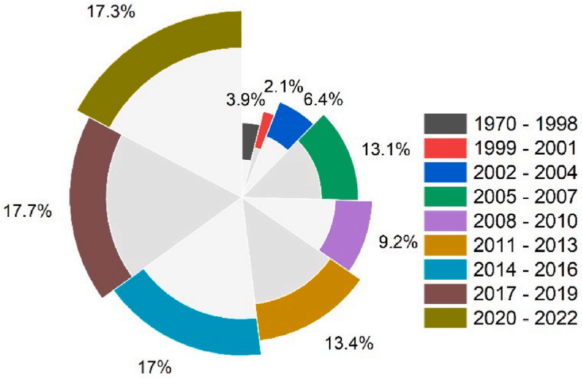

Fig. 2. The yearly distribution of the bibliographic records in the current study.

Therefore, relevant keywords were selected, e.g., indoor air quality, primary school, health impact, exposure risk, thermal comfort, pupils' performance, energy use in schools, and school ventilation. These keywords were searched in the journal title, abstract, and keywords for primary selection of peer-reviewed papers. To search conference papers, thesiss, standards, and technical guidelines, these keywords were searched only in the title. The selected studies were classified into specific categories according to the aim of the review. Fig. 1 shows the literature search overview with the selection criteria.

2.2. Year of publication

The publication year for the distribution of the collected bibliographic records on CAQ was studied. After eliminating duplication, all records were examined by their titles, keywords, and abstracts. The yearly distribution of published articles is shown in Fig. 2. The number of papers on CAQ showed an overall increasing trend, suggesting that the rate of research work in this area was growing over time. It can be concluded that people have started paying more attention to indoor air quality in schools with increasing demands of providing a healthy environment for children.

2.3. Country and region of publication

Fig. 3 represents the geographical distribution of articles summarized in the current study. Exposure risk and its impact on health and learning performance are attractive research problems. Energy consumption for improving thermal comfort and CAQ are commonly discussed research problems. Also, the effect of the outdoor environment on indoor ones has inevitably attracted researchers' attention around the world.

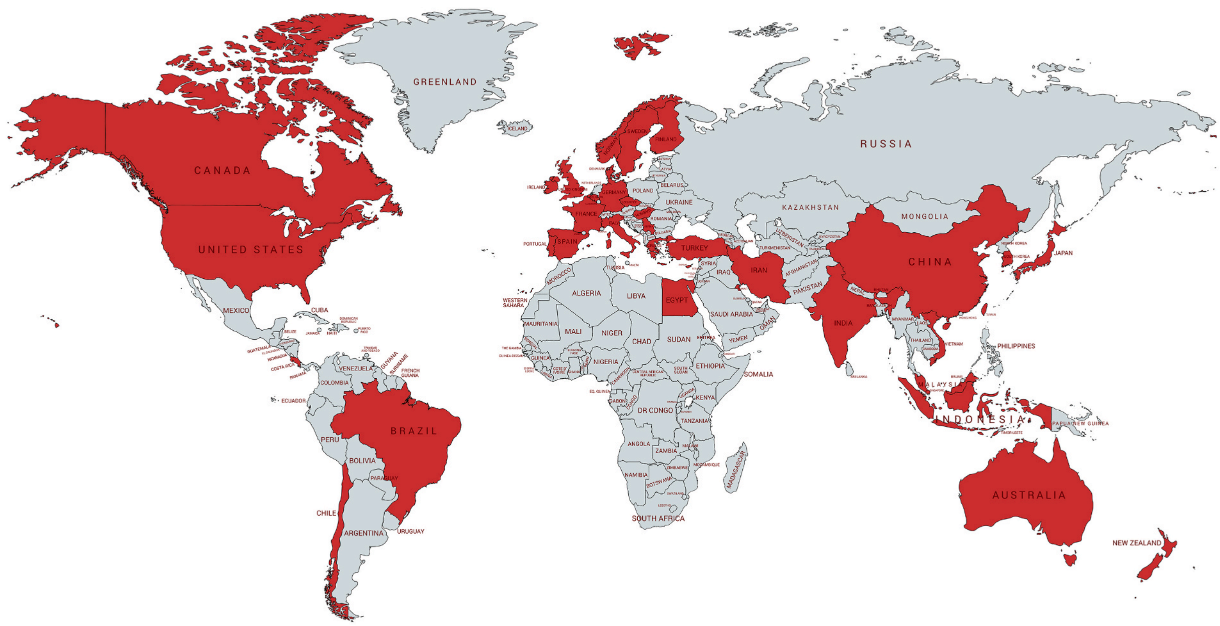

Fig. 3. The geographical distribution of research articles summarized in this study.

3. Analysis and discussion

3.1. Exposure risk in school classrooms

Pupils' exposure to indoor air pollutants in school buildings is a leading public concern and may cause severe damage to the pupils' health since they inhale a larger volume of air corresponding to their body weights than do adults [45–48]. The respiratory, immunological, reproductive, central nervous, and digestive system of childrens are not fully matured. The route of breathing, nasal versus oral, as well as the efficacy of the nose with aerosols, may also vary between children and adults, exposing children's lungs to higher quantities of air pollutants [49,50]. Some research studies have also confirmed the presence of animal dander allergens in school that might pose serious health issues in Pupils' with mild asthma and animal dander allergy [51,52].

Several research studies found that pollutant concentrations in schools were higher than concentrations in households and commercial buildings [53,54]. Children and adults bring chalk dust, fungi, bacteria, and viruses into the school environment, and vapors and odors from laboratories and art courses are also common sources of pollutants in schools [28].

Inhalation exposure to air pollution has increased children's mortality rate, acute respiratory disease, and asthma [45]. Due to different responses of the children's immune systems to indoor air exposures, various chronic diseases and symptoms have been reported and characterized as "sick building syndrome" [55]. Indoor pollution such as CO_2, PM, VOCs, NO_x, and ozone are recognized as indoor contaminants causing severe health problems for adults and children [56–58]. In general, the CAQ is characterized by a complex of contaminants, including VOCs, PM, aldehydes, bacteria, and molds [59,60]. Several studies have produced health risk assessments for the inhalation of indoor pollutants by considering various standards and recommendations, including the United States Environmental Protection Agency (EPA), WHO, ASHRAE, and GB/T [61–64].

3.1.1. Risk assessment

The U.S. EPA standards compute both the non-carcinogenic and carcinogenic effects of indoor air pollutants. The cumulative hazard index (HI) can be computed according to The National Air Toxics Assessment (NATA) U.S EPA, 2014 [65]. NATA air quality monitoring suggests the long-term risks to human health if air toxics emissions are steady over time. In this regard, summation of the hazard quotient (HQ) for the ith pollutant is considered as follows:

$$HI = \sum_i HQ_i = \sum_i \frac{ADI_i}{RfD_i} \tag{1}$$

where ADI_i is the daily average intake and RfD_i is the reference dose that has no negative impact on the human body. An HQ_i below one for the ith pollutant means zero increase in the occurrence of health problems.

The cancer risk (CR) is defined by the U.S EPA 2009 [3] standard to calculate the probability of cancer occurring during 70 years in a person exposed to carcinogenic materials. Although this method is not an accurate estimation for predicting the CR for exposed persons over time, it has been a common approach to evaluate the toxicity of various indoor environments [66–68].

The total CR due to exposure to air pollution is computed by Equation (2) below:

$$CR = \sum_i CR_i = \sum_i (LDI_i . CSF_i) \tag{2}$$

where the LDI_i is the lifetime daily intake defined as a dose of ith contaminant an individual is exposed to in 70 years. CSF_i is the cancer slope factor that calculates the carcinogenicity of the ith chemical substance that can cause cancer.

Schibuola et al. [64] evaluated the health risk of indoor air pollutants in school environments by adopting the HI and CR equations. They calculated the health risk of children's daily exposure to PM_{10} and CO_2. Applying the HQ equations for calculating the health risk has been validated by various research studies [69–71]. However, the health risk assessment results in Madureira et al. [72] showed the limitations in calculating HQ. The main weakness of HQ is its failure to consider the deposition area for particles in the respiratory system. Thus, it is challenging to define the health risk of various respiratory parts, including trachea, bronchia, etc., exposed to indoor air pollutants. It is important to notice that linking school environmental exposures to specific health symptoms is challenging because it is difficult to distinguish between school-based and non-school-based exposures, such as those caused by the home environment, regarding an observable health consequence [73].

3.1.2. VOC exposure

The VOC pollutants are among the leading indoor air pollutants causing severe health issues for children and adults. Construction materials, furnishings such as desks and shelves, resins of wood products, adhesives, glues, paints, cleaning chemicals, and carpets are primary VOC emission sources in schools [67,74–77]. The VOC concentrations in newly built or recently renovated school buildings may be significantly higher than ordinary ambient levels.

There has been a growing interest in evaluating the impact of exposure to VOCs on children's educational performance and health risk [78]. Kim et al. [79] studied the effect of microbial VOCs on asthma and atopy in 1482 pupils in eight schools in Sweden by using a questionnaire. Their results revealed a direct relationship between the concentration of the microbial VOCs and the presence of asthmatic symptoms in pupils. Johnson et al. [63] showed that lack of adequate air change and ventilation rates increased the concentration of the indoor contaminations, including VOCs, in the classrooms of twelve Oklahoma City schools.

The concentration of various VOCs, including formaldehyde, benzene, toluene, naphthalene, and xylene, has been monitored in different seasons during the year to evaluate the exposure risk level [9]. Another VOC found in schools is formaldehyde, which is frequently utilized to produce construction materials and a variety of other products [80,81].

Specific VOCs, such as benzene and formaldehyde, recognized carcinogens, have been strongly connected to health effects [82,83]. Sofuoglu et al. [84] showed that the formaldehyde concentration was the highest among the detected VOCs in three primary schools in Turkey. They characterized formaldehyde as a concerning pollutant with multiple carcinogenic risk levels in Turkish schools. Their results revealed that, besides formaldehyde, naphthalene, benzene, and toluene were indoor air pollutants with high concentrations. The measurement of fifteen typical VOCs concentrations in Minnesota (USA) schools showed that the exposure level of children to VOCs was higher in winter than spring [85].

High levels of VOCs in schools are suspected of causing irritation, throat dryness, allergies, and respiratory health problems [86,87]. Current asthma risk is raised by 1.3 when VOC concentrations are increased by 10 μg/m^3 [88]. Furthermore, TVOC levels are associated with chronic airway, general, and eye symptoms [89]. Daisey et al. [27] indicated that exposure to formaldehyde emitted by the polyurethane foams and adhesives causes eye, skin, and respiratory problems, which in severe cases can lead to asthma in children. However, exposure to persistent compounds (such as polycyclic aromatic hydrocarbons) can lead to specific types of cancer in individuals [27].

3.1.3. CO_2 exposure

The CO_2 concentrations are high in most school environments since a natural ventilation system is the primary approach to improving indoor air quality [30,90,91]. The indoor CO_2 level is not considered a pollutant by the WHO. While indoor CO_2 concentration is used as an indicator to evaluate IAQ [64], this meaning is commonly misinterpreted within the HVAC industry, despite efforts to address this confusion in standards, technical reports, conferences, and workshops [92].

Pupils' physical activity, window and door opening patterns in the classrooms, and ventilation performance can control the CO_2 levels in classrooms [61,93,94]. Awadi et al. [95] investigated the impact of CO_2 levels on the health risk of pupils in three schools in Kuwait. Their results showed a high concentration of CO_2 in classrooms, which indicated poor indoor quality, consequently increasing the health risk of pupils and reducing their educational performance. Madureira et al. [96] studied the relation between the indoor air pollution level and health issues, such as allergy and asthma, in primary schools in Portugal. Their measurements indicated that the concentration of CO_2 exceeded 1,000 ppm in highly occupied classrooms, thus decreasing the indoor air quality. CO_2 concentration data was used to evaluate airborne infectious diseases in 45 classrooms in 11 UK schools [97]. In this research, the variation in CO_2 concentration and ventilation rate affected the infection risk in different seasons with the greatest risk being in January.

Kalimeri et al. [47] measured various parameters in school environments in Greece. The parameters measured were, amongst others, CO_2 concentration, relative humidity, temperature, and formaldehyde, and it was reported that inadequate ventilation was a major indicator of bad indoor air quality. Turunen et al. [98] investigated IAQ and pupils' health for 6th-grade pupils in schools in Finland, and found a significant statistical correlation between temperature and self-reported bad indoor air quality. Another finding was that the lower the ventilation rate and the higher the temperature, the higher were pupil reports that the CAQ was poor. Smedje et al. [88] found no significant relationship between asthma symptoms and normal measured IAQ parameters, such as CO_2 concentration and humidity in Sweden. Simoni et al. [99] researched respiratory health for pupils in Norway and reported that children exposed to CO_2 levels above 1,000 ppm had a higher risk of having a dry cough. PM_{10} values above recommended levels also showed that nasal patency was lower than for children less exposed.

3.1.4. CO exposure

CO exposure is an acute hazard because it is odorless, colorless, and lethal. CO has been detected infrequently in schools with its primary source being automobile emissions [100]. When permitted, CO is mainly produced in school buildings by combustion sources such as heaters, gas and wood stoves, and smoking [101]. CO was found to be substantially linked with asthma and eczema [102].

3.1.5. NO_2 exposure

In the indoor environment, NO_2 emissions are produced by gas appliances, heaters, and cigarette smoking. These sources are **rare** in the majority of schools. Without interior pollution sources, NO_2 levels in classrooms are often associated with outdoor levels [103]. NO_2 concentrations in schools increased throughout the warmer season, enhancing greater NO to NO_2 conversion and resulting in O_3 production in the presence of VOCs and sunlight [28]. NO_2 exposure is associated with increased respiratory symptoms, allergy exacerbations (particularly to indoor allergens), conjunctivitis, wheezing, and itchy skin rash [104,105]. Exposure to higher indoor NO_2 concentrations in schools (higher than the 40 μg/m^3 limit recommended by WHO) was strongly associated with the prevalence of asthma and respiratory morbidity [29,104,106].

3.1.6. Ozone [O_3] exposure

Overall, outdoor O_3 concentrations are greater than those found inside schools [76,107]. In addition to filtration of the ventilation air as it enters the building, deposition on different solid surfaces, and chemical reactions in the indoor air result in a decreased indoor/outdoor ratio for O_3 in the school [107,108]. Lower indoor O_3 concentrations may also be caused by the absence of large sources in classrooms, such as photocopying machines or ozone generators [103].

WHO [82] recommended ozone values of less than 100 mg/m^3 for 8 h. However, the total evidence revealed that an increase in the range of 30–50 mg/m^3 could result in a minimum 6% rise in the relative risks of illness-related absence among pupils. Specific health effects accounting for absenteeism at elevated ozone levels are primarily related to respiratory illness, with the relative risk of respiratory diseases, wet cough, and nocturnal attacks of breathlessness [106,109,110]. Is it worth mentioning that ASHRAE Standard 62.1 requires mitigation of ventilation air if outdoor ozone exceeds 0.100 ppm (195 μg/m^3) [111].

3.1.7. PM exposure

Many schools have identified particulate matter (PM) pollution as a major source of indoor air pollution. Particulate pollutants come from various sources, including chalk dust, soil dust, new furniture, cleaning operations, particle resuspension due to pupil movements, combustion sources (including heaters, gas and wood stoves), smoking where permitted, and also outdoor sources (traffic, industrial emissions, and wild fires). However, Raysoni et al. [112] showed that the primary source of PM contamination in schools is outdoor air. Particles also enter schools via ventilation and infiltration from the outside environment, especially in metropolitan areas where automobile exhausts are the primary source [107,113,114].

Fine and ultrafine particulate matter may pose a serious health concern due to their origin in combustion processes [115]. Such pollutants can cause health issues, including asthma and respiratory system problems in children [116]. Various research results showed that PM could carry heavy metals and polycyclic aromatic hydrocarbons [117–119]. It is proven that inhaling PM causes greater risk to children than to healthy adults, owing to their lower fractional deposition efficiency and greater breaths/minute resulting from their lung size [120].

It was also reported that the concentration of PM_{10} particles increases in highly occupied classrooms. Moreover, high levels of pupil activity increase PM levels in the air due to the resuspension of particles already present on surfaces [121].

Exposure to heavy metals and the contaminants carried by PM_{10} particles increases the risk of respiratory sickness, and lung cancer among pupils [72]. PM_1 exposure at school had toxicological consequences, mostly on baseline lung function in children with chronic respiratory illness [122]. Exposure to mean $PM_{2.5}$ concentrations in the range of 20.5 ± 2.2 mg/m^3 was linked to conjunctivitis, hay fever, an itchy rash, and sensitization to outdoor allergens [104]. Fonseca et al. [71] investigated the impact of particle contamination exposure doses in preschool children in Portugal. Their results revealed that children attending schools in urban areas were exposed to a higher level of PM contamination due to higher traffic density.

3.1.8. Fungi and bacteria exposure

Penicillium, Cladosporium, Aspergillus, and *Alternaria* are the most common fungi found in indoor school environments, and their prevalence varies depending on climate and location, whether rural or urban. According to several studies [123–125], the mean total indoor fungi concentrations (CFU/m^3) in school classrooms ranged from 92 to 505 colony-forming units (CFU). Numerous studies have found positive relationships between exposure to fungi particles at mean concentrations of 260–1297 CFU/m^3 with general and respiratory symptoms among pupils [106,126]. Incidence of wheezing, asthmatic attacks, headaches, sore throat, weariness, and coughing were also reported in schools as severe general symptoms of fungi in the school buildings [106,126].

Bacteria concentrations ranged from 250 to 17,000 CFU/m^3 in schools [79], and *Staphylococcus, Corynebacterium,* and Bacillus are the most commonly found types [127]. Although exposure to damp buildings has been shown to increase the risk of developing health problems, there is no explicit minimum threshold for microbiological concentrations and microbial by-products. Bacteria have been associated with the current risk of asthma and nocturnal breathlessness [79]. According to the "hygiene hypothesis", exposure to low microbial concentrations and endotoxins may protect pupils from school respiratory symptoms and asthma [79,127,128].

3.2. Ventilation in classrooms

ASHRAE Standard 62.1 recommends a minimum ventilation rate of 6.7 L/s-person for classrooms (5 L/s-person + 0.6 L/s-m^2, assuming the default occupant density of 35 person (age 9+) in 100 m^2) [111]. Increases in ventilation rates of up to 20 L/s per individual have been found to reduce the prevalence of sick building syndrome symptoms and enhance IAQ [129]. Poor ventilation rates in classrooms influence not just the comfort and health of pupils but also their learning performance [130]. According to Shaughnessy et al. [131], there is a negative relationship between pupils' math standardized exam results and ventilation rates.

In general, specific air pollutants may cause significant and persistent immunosuppressive reactions, leading to increased infectious diseases and neoplasia (abnormal benign or malignant cell growth) [132]. School absenteeism can be correlated with low air quality and pollution problems [133]. The sources are multiple, and standard do not always ensure the acceptable pollution levels. A range of significant pollutants (CO_2, Particulate matter ($PM_{2.5}$, PM_{10}), Total volatile organic compounds (TVOC), and a set of specific volatile organic compounds (VOC) including aldehydes) was identified as critical for educational building environments in nine Mediterranean schools [134]. Also, $PM_{2.5}$ and nitrogen dioxide (NO_2) were found to have similar dynamics in 109 French schools due to their outdoor sources whilst certain classes of pollutants, such as the VOCs, are less easily treated since they are more likely to vary in concentrations within the indoor premises and may not be controlled at all [135]. Moreover, it was demonstrated that most poor indoor air quality is highly correlated with outdoor pollution levels [136–138]. Thus, the presence of pollutants specific to the outdoor environment, like NO_2, equivalent black carbon, $PM_{2.5}$, the number and concentration of ultrafine particles, road-traffic-related trace metals, and particularly the particulate matter, underscores the need to consider mandating proper filtration of the fresh air intake.

Moreover, the pandemic period has highlighted the importance of proper ventilation, air distribution, and effective air change in schools [139–141] since in crowded indoor settings, infectious diseases can propagate faster, and children are usually a transmission vector towards families, even when the symptoms are milder in a younger population [142]. The long period of time spent in classrooms significantly increases the risk of infection, risk also observed in the case of other types of high density occupancies (e.g. restaurants, public events, or public transportation), especially when inadequate ventilation and air distribution systems are in place [143]. Additionally, one of the most encountered pollutants in schools, $PM_{2.5}$ [144], has a positive association with the spread of COVID-19, as it can act as a nucleation site to transport viruses directly into the respiratory system [145]. This could also be due to an inadequate ventilation rate.

Current norms and guidelines for the ventilation of educational buildings differ among countries and regions. In general, a minimum airflow rate per person and/or per floor area unit is required to dilute the air pollutant concentrations to a specific level of air quality. Usually, the ventilation rate is expressed in L/s (m^3/h) per person or L/s (m^3/h) per m^2 floor area. However, these minimal requirements may not address specific occupancy types, levels of activity, or types of pollutants, leading to ventilation rates in classrooms that are often lower than the minimum ventilation rates specified in building codes and standards [146]. Furthermore, the maximum concentration of CO_2 in classrooms might vary by different standards, however, the upper threshold is about 1,000 ppm [147–149]. However, it remains the primary indicator for IAQ level, even if other pollutants or respiratory airborne transmission contaminants pose higher risks to the occupants. So far, there is a clear knowledge gap related to ventilation constraints necessary to provide acceptable safety concerning airborne transmissible diseases in classroom environments but to consider at the same time other types of concerns like air pollutants (chemical gaseous and particulates) or energy efficiency. Comprehensive ventilation strategies are needed to tackle infectious respiratory risks and provide pupils with healthy CAQ conditions [150].

Due to high occupancy rates, it is mandatory to provide classrooms with ventilation systems that can deliver outdoor air to the breathing zone, prevent indoor cross-infection, and dilute pollutants. Ventilation strategies can be classified as natural, mechanical (unidirectional and bidirectional flow), or hybrid ventilation, which represents a combination of systems designed to supply interior spaces with (filtered) outdoor air and to extract polluted indoor air. An adequately controlled hybrid ventilation system operating in mechanical supply mode can provide adequate ventilation and effectively decrease the concentrations of some indoor-generated pollutants [151]. The mechanical supply should function in heat recovery mode in colder periods and when avoiding overheating is necessary. Usually, old schools are not equipped with mechanical ventilation, relying on natural ventilation (natural driving forces), which require careful management of opening windows to be effective [152]. However, the COVID-19 pandemic has generated an increased awareness of the need for proper ventilation, and national and international guidelines have been released to promote rigorous natural ventilation plans [153].

Natural ventilation is the most common type of ventilation system used in educational buildings, being predominant in the US, Southern, and South-Eastern Europe, China, India, Australia, etc. [16], while the Nordic countries have similar percentages of mechanical or hybrid ventilation versus natural ventilation. The UK has a significant percentage of schools naturally ventilated, the mechanical ventilation systems being present in approx. 12% of the buildings [150], while Canada is intensely investing in equipping all educational buildings with heating, ventilation, and air conditioning (HVAC) systems, given the recent pandemic concerns.

Ensuring good CAQ depends on several factors. The air distribution system has an important function in introducing the outdoor air into the classroom. When a mechanical ventilation system is in place, mixing ventilation (MV) systems are used for fresh air provision in classrooms and the dilution principle is applied. However, studies indicate that other air distribution systems (displacement or personalized ventilation) can provide efficient ventilation in classrooms, considering the constraints of infectious respiratory diseases.

Several studies indicate that existing ventilation methods are not appropriate for preventing short-range airborne transmission of respiratory droplets between indoor occupants (even more so if the occupancy rate indoors is high), and new intervention methods, for example, personalized ventilation, which delivers fresh air in the breathing zone, are recommended [154,155]. However, personalized ventilation should complement other HVAC systems, and complex installation is needed if this was not considered at the concept phase of the building. Additionally, local discomfort can be felt by the users [156].

Displacement Ventilation (DV) has a higher ventilation efficiency in the occupant zone [25,26] and is characterized by a low momentum flow. Compared with mixing ventilation, DV provides better air quality in the occupation zone. The type of supply air diffuser does not seem to be of significant importance as long as the principle of displacement is respected. However, the system is efficient when the supply operates in isothermal conditions or with cooler airflow, while for heating mode, complementary or adjustable systems are necessary [157]. Moreover, the children can feel thermal discomfort at specific air velocities. When increasing the momentum, a hybrid system replaces the DV with a confluent jet system, which performs slightly better for higher heat loads [158,159]. The stratum ventilation system also brings fresh air into the breathing zone, allowing the inlet air to flow out horizontally [160]. Though, in the case of schools with high occupancy, the crossflow infection risk for highly contagious diseases could be substantial.

Another low momentum system is represented by an underfloor air distribution system which can perform better in the case of airborne infection risk due to vertical flow. For such reasons, it is required that the exhaust outlets should be far away from the breathing zone of the occupants, and special attention should be given to teachers who are usually standing [161]. Nevertheless, in such cases, the dust and particles on the ground can be driven into the flow.

3.3. Thermal comfort in school classrooms

Indoor thermal conditions in classrooms are particularly significant as school children are more vulnerable to adverse environmental stimuli than adults [2,162–164]. Research literature reports physical and physiological differences between children and adults, including different surface-area to mass ratios, sweating rates, metabolism, body temperature, and cardiac output [165–167]. Havenith [165] collected data on the metabolic rate of Dutch school children in classrooms and found their metabolic rates (watts per square meter body surface area) were lower than an adult for a similar level of activity [164]. For instance, the metabolic rate of senior primary school children (i.e. 10-11 year olds) for passive activities in the classroom ranging from 62 to 64 W/m^2 is 10% lower than the values for office sedentary activity (i.e. 70 W/m^2) stipulated in ISO 7730 [168]. Children have a larger ratio of body surface area to mass compared to adults; the surface-area to mass ratio of an 8–9 year old child (e.g. 130 cm, 20 kg, 0.87 m^2) can be 40% greater than that of an adult (e.g. 175 cm, 67 kg, 1.81 m^2) [169]. Also, children have a lower sweating rate (which is proportional to metabolic rate) [166,169] and lower cardiac output [167].

Aside from the physical and physiological differences between children and adults that may influence their thermal regulation and perception, distinctive contextual factors should also be considered [170]. Adjusting clothing based on indoor and outdoor temperatures is an important method to help occupants adapt to the surrounding thermal environment. However, Kim and de Dear [171] found that Australian pupils' clothing insulation remained almost unchanged across the entire range of indoor and outdoor

Table 1
The effects of indoor air quality in classrooms on cognitive performance and learning by children [38].

Study	Classroom air quality (CAQ)	Measurements of cognitive performance or learning or absence rate	Major results
Myhrvold et al. [185]	CO_2: 1500–4000 vs. <1000 ppm	Simple reaction time.	Reduced CO_2 levels improved performance.
Ribic [186]	CO_2: 3800 to 870 ppm	Concentration and attention (d2-test).	Reduced CO_2 improved performance.
Sarbu and Parcurar [187]	CO_2: 2000–500 ppm	Concentration and cue-utilization (Kraepelin and Prague tests).	Reduced CO_2 improved performance.
Coley et al. [188]	CO_2: 2900 to 690 ppm	Reaction time.	Improved performance at lower CO_2 levels.
Bakó-Biró et al. [184]	1 L/sp to 8 L/sp (1500–5000 to <1,000 ppm)	Reaction time, concentration and attention, recognition and memory.	Improved performance at a higher ventilation rate.
Mattsson and Hygge [189]	Reduced particle levels and cat allergen.	Five performance tests.	Finding synonyms improved but most likely due to chance.
Hutter et al. [190]	Reduced levels of tris(2-chlorethyl)-phosphate (TCEP) in PM_{10}, $PM_{2.5}$, and dust; and CO_2.	Reasoning component of general intelligence (Standard Progressive Matrices).	Cognitive performance improved with reduced levels of pollutants.
Wargocki and Wyon [191]	Ventilation rate between 3 and 10 L/sp.	Arithmetical calculations and language-based tasks.	The speed at which tasks were performed improved with no effects on errors.
Bakó-Biró et al. [184]	Ventilation rates changed from 0.3 to 0.5 to 13-16 L/sp.	Arithmetical calculations and language-based tasks.	Task performance improved with increased ventilation.
Petersen et al. [192]	Ventilation rates changed between 1.7 and 6.6 L/sp.	Arithmetical calculations and language-based tasks.	Performance of addition, number comparison, grammatical reasoning, and reading and comprehension improved at a higher ventilation rate.
Hviid et al. [193]	The ventilation rate changed from 3.9 to 10.6 L/sp.	Arithmetical calculations and language-based tasks.	Processing speed, concentration, and mathematical processing improved.
Wargocki et al. [194]	Concentrations of airborne particles reduced in all size ranges and reduced settled dust on horizontal surfaces.	Arithmetical calculations and language-based tasks.	No effects on cognitive performance.
Haverinen-Shaughnessy et al. [195]	Different CO_2 levels corresponding to ventilation rates up to 7 L/sp.	Language and mathematical examinations.	3% more pupils passed the tests for every 1 L/sp increase in ventilation.
Haverinen-Shaughnessy and Shaughnessy [182]	Different CO_2 levels corresponding to ventilation rates up to 7 L/sp.	Mathematical scores.	Math scores improved by 0.5% for every 1 L/sp increase in ventilation.
Mendell et al. [196]	Ventilation rates and CO_2 levels.	Scores in mathematics and English.	A 10% increase in ventilation resulted in a 0.6 point increase in the score obtained in the English test.
Toftum et al. [197]	Classrooms with natural ventilation, exhaust ventilation, and mechanical ventilation systems.	Academic achievements (Standardized Danish test scheme) – mainly language-based and math tests.	The lowest scores were observed in naturally ventilated classrooms with the highest CO_2 levels.
Gaihre et al. [198]	CO_2: 600 to 2,100 ppm	Educational attainment measured as the % of class attaining the average level expected for the group.	No relationship was observed between CO_2 levels and educational attainment.
Kabirikopaei et al. [199]	Ventilation, particle levels, ozone.	Reading and mathematical scores.	Scores higher with increased ventilation rates. Fine particles were associated with math scores and ozone with reading scores.
Lau et al. [200]	Presence of unit ventilators.	Reading and mathematical scores.	Presence of unit ventilators associated with higher coarse particles, lower ventilation rates, higher noise, and lower mathematics scores.
Murakami et al. [201]	Ventilation rate changed between 0.4 and $3.5h^{-1}$.	Learning by college pupils.	Learning improved with increased ventilation.
Ito et al. [202]	Ventilation rate changed between 0.4 and $3.5h^{-1}$.	Learning by college pupils.	Learning improved with increased ventilation.
Pilotto et al. [203]	Pollutants from gas heaters.	Attendance in schools.	The presence of pollutants reduced attendance.
Berner [204]	School maintenance.	Academic achievements.	Poor maintenance reduces academic achievement.
Ervasti et al. [205]	Perceived air quality.	Short-term sick leave.	Sick leave (of teachers) increased with poor perceived air quality.
Shendell et al. [206]	CO_2 concentration.	Sick absence.	Pupil absence decreased by 10–20% when the CO_2 concentration decreased by 1,000 ppm.
Gaihre et al. [198]	CO_2: 600 to 2,100 ppm	Absence rates.	An increase of 100 ppm of CO_2 corresponds to a 0.2% increase in absence rates.
Simons et al. [207]	Poor ventilation.	Sick absence.	Higher sick absence linked with poor ventilation.
Kolarik et al. [208]	CO_2 below 1000 ppm (average 640 ppm).	Sick absence (day-care centers).	Increasing the air change rate by 1 h^{-1} would reduce the number of sick days by 12%.
Mendell et al. [209]	CO_2 levels.	Illness absence.	Illness absence decreased by as much as 1.6% for each additional 1 L/s per person of the ventilation rate.

(*continued on next page*)

Table 1 (*continued*)

Study	Classroom air quality (CAQ)	Measurements of cognitive performance or learning or absence rate	Major results
Deng and Lau [210]	Different parameters characterizing CAQ.	Illness-related absenteeism.	Presence of fine particles during the cooling season increased absence rates, while the increased absenteeism during the heating season was caused by reduced ventilation (indicated by the increased CO_2 levels).

temperatures during the whole survey period in subtropical Sydney, perhaps because of the presence of a school uniform dress code or peer group norms. In addition to the reduced degrees of freedom for clothing adjustment, the possibilities of modifying activity level (metabolic rate) or adjusting environmental variables (e.g. opening windows or doors, using fans, etc.) are limited for pupils during lessons. Pupils in classrooms are not active users of the environment but rather passive recipients of the conditions. Teachers are active users, but they are more likely to adjust classroom temperatures based on their thermal preferences rather than those of pupils.

Haddad et al. [172] discussed Iranian pupils' thermal comfort and confirmed that children's thermal neutrality was a few degrees lower than adults under identical thermal conditions, which could be due to a difference in their metabolic rate level. Similarly, Kim and de Dear [171] collected 4866 responses from school classrooms in Australia across two summer seasons. They found that the pupils generally preferred "cooler-than-neutral" sensations. The preferred temperature was estimated to be 2–3 °C below the neutrality predicted for adults under the same thermal environmental exposures. Studies in Chile [173] and the Netherlands [174] also indicated lower comfort temperatures of pupils compared to adaptive models. Dorizas et al. [175] investigated CAQ in schools and found that a temperature of 22.31 °C made the pupils feel satisfied, while temperatures above 25 °C made them feel dissatisfied.

On the other hand, Liang et al. [176] found the neutral temperature for the pupils in the hottest month in Taiwan to be up to 29.2 °C, which is higher than the corresponding value stipulated in the ASHRAE Standard 55 [177]. According to recent reviews [178,179], the general consensus is that school pupils tend to feel comfortable in indoor climates that are "slightly cooler" than the adult thermal neutralities observed in office settings.

A high-quality classroom thermal environment should benefit pupils' academic performance. It is suggested that the magnitude of the negative effect of classroom temperature on performance was, for some tasks, as high as 30% [180]. Still, there are few studies on direct associations between indoor classroom thermal conditions and performance [2]. Romieu et al. [181] found a connection between temperature and absenteeism for respiratory illness. The probability of absenteeism was 1.28-fold higher in high-exposure compared to low-exposure pupils. There are two competing schools of thought on the relationship between temperature and performance.

Five decades ago, Wyon conducted an experiment with Swedish children under three classroom temperatures, concluding that children's performance of school exercises was significantly lower at 27 °C and 30 °C in comparison with 20 °C [180]. Haverinen-Shaughnessy and Shaughnessy correlated state-wide assessment of learning with measured classroom temperatures, finding a 13% increase in math scores for every 1 °C decrease of classroom temperature [182]; however, the state-wide assessment was not always on the same day that the temperature measurement was carried out, making their conclusions about temperature-performance relationships tenuous. Porras-Salazar et al. [183] found the neutral temperature for pupils in a tropical climate to be 27 °C and a slightly cool environment most conducive to the performance of schoolwork to be 25 °C. Wargocki et al. [17] examined all studies on the effect of thermal environment on pupils' performance and found that temperatures below 22 °C would be optimal. However, it is hard to reach a consensus with limited studies reflecting the direct associations between indoor classroom thermal conditions and performance so more research is needed to confirm the most appropriate model to guide the design and operation of the classroom environment.

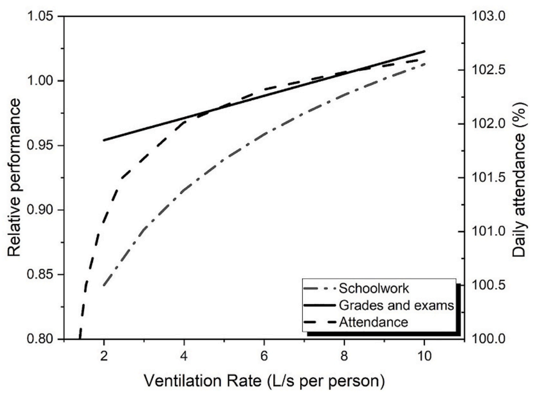

Fig. 4. *Performance of schoolwork (speed), national and aptitude tests and exams, and pupils' daily attendance as a function of classroom ventilation rates* [17].

3.4. Pupils' performance and classroom air quality

3.4.1. Classroom air quality and cognitive performance

Most of the studies investigating the effects of CAQ on cognitive performance are summarized in Table 1. These studies confirm that poor air quality affects both typical schoolwork of pupils, i.e. performance in simple learning tasks such as math and language exercises and pupils' examination grades and end-of-the-year results. Some studies observed that poor CAQ also increased absenteeism, a marker of health effects and their impact on proper learning.

Low classroom ventilation rates can impair pupils' attention and vigilance, lowering memory and concentration [184]. This study showed that in poorly ventilated classrooms, pupils are likely to be less attentive. The magnitude of the adverse effects of inadequate ventilation was even higher for tasks that require more complex skills such as spatial working memory and verbal ability to recognize words and non-word data.

Wargocki et al. [17] analyzed all published evidence on the effects of CAQ where the measurements of CO_2 (a proxy for classroom ventilation) were reported along with the cognitive performance of pupils. They aimed to establish the impact of the indoor environment parameters on pupils' performance and attempted to identify the minimum air quality levels needed to avoid the risk of reduced performance. They separately analyzed the results from the studies examining schoolwork, grades and exams, and absence rates. In the absence of an air quality metric, they used CO_2 as an indicator of IAQ (ventilation).

Fig. 4 shows the relationships established by Wargocki et al. [17]. They concluded that increasing the ventilation rate in classrooms to 10 L/s per person would bring significant benefits and improve learning and reduce absenteeism. It was found that the CO_2 concentration should be kept at or below 900 ppm. No data could be found on whether CO_2 levels lower than 900 ppm or ventilation rates higher than 10 L/s per person would bring additional benefits. However, considering that the relationship between the performance of office work and ventilation is log-linear [211], it is likely that additional ventilation improvements would bring further benefits, as also suggested by the relationships presented in Fig. 4.

3.4.2. Social impact of classroom air quality

There are very few assessment studies on the impact of improving CAQ on socio-economic benefits. Wargocki et al. [212] estimated the benefits of improved ventilation in Danish classrooms. Assuming that all Danish classrooms are ventilated at a rate of 6 L/s per person, which is the case for about 50% of classrooms [197], an assessment was made of the benefits that might be obtained if the ventilation rate is increased to 8.4 L/s per person, which is the requirement in Sweden. Using the Danish Rational Economic Agency Model (DREAM) and data from Chetty et al. [18], it was estimated that improvements in ventilation would yield an average annual increase in the gross domestic product (GDP) of €173 million and an average annual increase in the public budget of €37 million in the following 20 years. The impact is generally due to more pupils completing their education under favorable learning conditions. These estimates were based on increased productivity in adult life due to better exam grades in school, fewer pupils staying longer in elementary schools (which is a non-compulsory 10th grade in Denmark), resulting in overall shorter education periods, reducing the period for joining the job market, and reduced teacher sick leave.

It is well established that indoor air quality improves by increasing the outdoor air supply rate. There are also studies showing the benefits of using mechanical ventilation systems in schools [213]. However, very limited data exist on the effects of using other approaches to control sources of pollution in classrooms or the use of air purifiers [214].

3.5. Energy and classroom environment quality

Worldwide energy consumption is continually growing, and a large proportion of this growth is associated with non-domestic buildings which consume 11% of European and 18% of the USA's total energy [215].

The most influential factors in building energy consumption have been reported by Yu et al. [216]: 1) Climate; 2) Occupant behavior; 3) Building-related; 4) User-related; 5) Service and operation of the building; 6) Social and economic factors; and 7) The required indoor air quality. All of these parameters can contribute to higher or lower energy consumption. Building-related parameters can be age, orientation, window-to-wall ratio, area, leakage of the building envelope, and U-value. The service and operation of the building also influence energy consumption. This can be the operation time of the HVAC system, maintenance procedures, and the age of the system [216].

3.5.1. Breakdown of energy consumption

Although some benchmarks provide category energy breakdowns (e.g. lights, cooling, heating, ventilation), such data still fail to show the yearly energy consumption associated with each category. Norwegian Standard NS 3031:2014 [217] presents a breakdown of energy consumption into six categories, distinguishing between thermal energy needs (Categories 1, 2, and 3) and electricity-specific energy needs (Categories 4, 5, and 6). These energy posts can generally be simulated in software with standard values from NS 3031:2014. On the other hand, field measurements of energy per purpose are often impossible because some buildings are not equipped with detailed sensors [218]. Sometimes buildings are equipped with sensors to measure energy consumption, but there can be problems with data communication. Ouf and Issa [219] state that different metrics serve various purposes and presented results on the same data set by analyzing energy consumption per occupant and per floor area at schools in Manitoba, Canada. This study shows that middle-aged schools consumed the most energy when using energy consumption per floor area. Analyzing energy consumption per occupant, the oldest schools consumed the most energy.

3.5.2. School buildings' energy consumption

There have been many reports summarizing the energy consumption of school buildings in various countries and regions worldwide. According to the National Center for Education Statistics, almost 100,000 public K-12 schools representing 5% of commercial building energy consumption expend $8billion in utility bills and serve 50 million students plus three million teachers. A report from Texas found that 71% of school units use $70–200 of energy per pupil [220]. The annual energy consumption of primary and secondary schools in the eight US climate zones are 173 kWh/m^2 and 257 kWh/m^2 respectively [221]. In China, a survey shows that the total annual energy consumption of school buildings in the cold region is about 103 kWh/m^2, and the average annual power consumption per unit area of the surveyed public buildings is 24.31 kWh/m^2 [222]. However, school buildings' average annual power consumption in temperate regions is about 30.61 kWh/m^2, which is slightly higher than the national average of 29.6 kWh/m^2 [223]. In Hong Kong, the reported comprehensive annual energy consumption of school buildings is 105.61 kWh/m^2 [224].

Most Norwegian schools have high energy needs for ventilation, heating, and a minimum of cooling demand. The report highlights the increasing cooling need because of increasing heat-generating ICT (Information and Communications Technology) infrastructure in schools [218]. Kilpatrick and Banfill [225] have collected energy data from 48 schools, including 32 Secondary schools, 11 primary schools, and five specialized schools, and showed when and how much energy is used in a wide range of schools (see Table 2).

The average specific energy consumption for schools in Norway is reported as 170 kWh/m^2 per year. The total energy consumption includes space heating, ventilation, hot water, ventilation aggregates, lighting, and other electricity use. Ding et al. [226] investigated 40 schools connected to the district heating grid in Trondheim. The main finding was that the predicted annual demand for district heating and electricity was respectively 72 kWh/m^2 and 57 kWh/m^2. This gives a total annual energy consumption of 129 kWh/m^2.

In a recent publication [227], the annual energy consumption value presented for Cyprus schools, based on billed energy, is 62.75 kWh/m^2 and 116.22 kWh/m^2, when expressed in primary energy.

The topic of energy relating to Hellenic schools has been abundantly published [228–234]. Greek climatic zone definitions have been changed. There were three climate zones within the previous regulation (TIR) (A–C). KENAK introduced an additional climate zone (D) within the northern regions of the country (zone C) [234]. In 2011, Dascalaki and Sermpetzoglou [229] undertook a comprehensive study aiming at assessing the energy performance of schools on a national level, embracing the three climatic zones (A–C). The collected data was used to define "typical" values, in other words, energy performance benchmarks. From a total selection of 500 schools, the average thermal, electrical, and total annual energy consumption was found equal to 57, 12, and 69 kWh/m^2, respectively.

In March 2012, in a press release reported by the Paris mayor, the energy profile of schools in this city was revealed as 224 kWh/m^2 [221]. The value presented is expressed in primary energy comprising all the energy consumption in the Parisian schools (half of which were constructed between 1880 and 1948).

In North America, a reference table for Canada has been designed for different buildings to help balance their energy use to the national median. Herein, the recommended benchmark metric is the national median source – Energy Use Intensity (EUI), expressed in GJ/m^2. The median EUI value is 197 kWh/m^2. Since site EUI results in a mixture of energy (primary and secondary energy, depending on the type of energy provided to the building, e.g. raw fuel like natural gas vs. a converted product like electricity), the use of source EUI is recommended (the median of 283 kWh/m^2) [235].

The values presented by Kim et al. [236], relating the average energy consumption of the elementary schools in South Korea, are expressed in MJ/m^2 in terms of annual energy use (electricity, oil, and gas) and *per capita*, ranging between 2,951MJ/pupil to 3, 889MJ/pupil. The sum of the three fuel types (energy consumption per unit area) was determined as 101.4 kWh/m^2, 72% of which corresponds to electric energy use.

3.5.3. Indoor environment and energy consumption

The Energy Efficiency–Thermal Comfort–Indoor Air Quality dilemma is a relationship discussed in the research, amongst others [237]. It is essential to investigate and establish this relationship because energy efficiency measures in a building cannot be at the expense of the indoor environment. Zhang and Bluyssen [238] studied the indoor environment and energy consumption at nine primary schools in the Netherlands. Energy consumption was analyzed and categorized based on total energy consumption per category: year of construction, area, number of occupants, and ventilation system. The low-consumption buildings were the newest with fewer occupants, while the high-consumption schools were older, with more occupants. The low energy consumption schools had lower measured relative humidity than the high-consumption schools.

Pearson's correlation coefficient was used to assess potential correlations between energy consumption, measured indoor environmental parameters, and perceived indoor climate based on user satisfaction surveys. They concluded that the higher the electricity consumption, the more pupils complained about the IAQ. In general, they uncovered more complaints in the high-consumption schools. None of the correlations between measured indoor environment and energy consumption was found to be significant. The researchers recommended a higher resolution analysis.

Table 2
School details investigated by Kilpatrick and Banfill [225].

Year	FA (m^2)	TEU (kWh)	Year	FA (m^2)	TEU (kWh)	Year	FA (m^2)	TEU (kWh)	Year	FA (m^2)	TEU (kWh)
1960	2535	195,221	1960	15368	695,154	1960	9561	888,443	1960	11852	605,890
1980	9835	342,507	1970	11535	643,994	1930[a]	14909	687,511	1979	10156	492,587
1989	11430	512,819	1893[a]	11742	565,302	1940[a]	13559	607,708	1975	11927	945,627
1991	12349	863,421	1978	11436	1,433,075	1940[a]	11052	730,518	1960	1225	235,543
1954	13145	441,056	1965	11918	584,281	1950	14265	602,720	1980	7871	354,727

[a] School built at this date, but renovated after 2000; FA (Floor Area); TEU (Total Energy use).

A study from Gothenburg investigated 30 schools regarding yearly energy consumption per unit floor area and indoor environmental parameters [239]. Ventilation categories of the investigated schools were: (A) natural ventilation, (B) balanced ventilation with constant air volume (CAV), and (C) balanced ventilation with variable air volume (VAV) or demand-control ventilation (DCV). Based on field measurements of CO_2 concentration, temperature, and added humidity, this study reported a negative correlation between the year of construction and yearly energy use [kWh/m^2] in the whole sample. The weekly average temperature and energy performance for category A was positive and weak. For categories B and C, it was negatively solid and significant. The weekly average CO_2-concentration and energy performance found weak and insignificant relationships. This showed that the correlations were sporadic and differed over the categories. Other studies also showed that DCV could reduce energy consumption [240]. The measurements show that in all the case studies, the DCV system delivered and maintained good IAQ, even at reduced airflow rates [241]. Results of the case studies show that significant reductions in energy consumption are achieved for both the fans (50–55%) and ventilation heat losses (34–47%) [242].

Diffuse ceiling ventilation works through the low-impulse supply of air through the perforated panels installed as the suspended ceiling and was also subjected to investigation in many studies [243–247]. This ventilation system is proven to provide a good IAQ while lowering ventilation energy consumption.

Allab et al. [248], Ghita and Catalina [249], Dascalaki and Sermpetzoglou [229], and Pereira et al. [250] also investigated energy consumption and IAQ. A recent review article [44] suggests that control based on the internet of things (IoT) or artificial intelligence (AI) could be an effective method of providing optimized solutions for mixed ventilation strategies to balance natural and mechanical ventilation types in school buildings.

3.6. The impact of the outdoor environment on classroom air quality

The WHO indicates that all non-communicable diseases together accounted for 74% of the total deaths globally in 2019 [251]. Comparing different global risk factors shows that ambient air pollution is a leading cause of excess mortality and decreased life expectancy [252]. Air pollution was even more of a serious health problem than COVID-19 in 2020 [253].

Outdoor air pollution impacts IAQ using air change rates, including natural ventilation, mechanical ventilation, and infiltration [12,254–257]. Meanwhile, some pollutants are brought indoors through people's activities; for example, environmental bacteria and particles are transferred from shoes onto floors and carpets [254,258]. The main influencing factors can be grouped into outdoor contaminant concentrations and meteorological conditions [259,260].

3.6.1. Outdoor contaminant concentrations

For schools, outdoor air pollutant sources, such as high-density traffic areas or industrial and construction activities, play an important role in final IAQ performance [134]. Studies have shown that numerous schools are located in areas with high levels of air pollutants [136,261,262]. The school's geographical location plays a significant role in formulating its indoor and direct outdoor air quality.

Many field tests have measured indoor and outdoor air quality in schools near particular locations such as industrial areas [263–265], transportation zones [266], and port areas [267]. The indoor air quality in a primary school located near a high-impact industrial site in Italy was assessed. The VOC concentrations were in line with or above those of other studies conducted in the same condition [264]. High metals and polycyclic aromatic hydrocarbon concentrations were detected, especially when schools were downwind of a steel plant. The indoor/outdoor (I/O) ratio showed the impact of outdoor pollutants, especially of industrial markers, such as Fe, Mn, Zn, and Pb, on indoor air quality [265]. A classroom near a busy intersection on a main arterial road was monitored. It was found that the by-products of motor vehicle emissions were the main contributor to indoor $PM_{2.5}$ [266], black carbon, and nanoparticles [268]. Similar results were obtained for schools in Greece and New Zealand, where combustion products from vehicles are the critical source of airborne particles [269,270].

3.6.2. Meteorological conditions

The outdoor temperature, relative humidity, and wind speed affect I/O ratios [271]. Based on air pollution monitoring area data, a strong correlation between air pollutants and meteorological indicators was observed [272]. In non-winter periods, the outdoor temperature is higher than that indoors. This creates a thermal gradient, and so the outdoor air flows indoors, increasing the I/O of particulate matter [273]. The higher humidity during non-winter seasons reduces the outdoor particulate matter concentrations and increases the I/O ratio [274]. Further, higher wind speed increases the infiltration of outdoor particulates indoors. Correlation analyses show that outdoor meteorological factors affect indoor $PM_{2.5}$ concentrations [275]. Hence, meteorology plays a vital role in the migration of particulate matter indoors [276].

Airtight buildings have grown rapidly in order to conserve energy, to reduce the infiltration of outside air, and to make circulation of inside air in the occupied zone. There is a nexus between the ventilation and indoor air quality in buildings [277] as while airtight buildings can help conserve energy, they accumulate pollutants inside. The use of natural ventilation not only provides acceptable IAQ levels but also reduces energy use given the consequent reduction in the use of mechanical ventilation [278]. Outdoor pollution should be accounted for when making decisions on using a natural ventilation strategy. This is especially true for developing countries [279]. Hence proper management for school building characteristics is needed. Considering the mentioned problems, it is essential to develop practical methods of providing pollutant concentrations using the limited information available from public sources [280]. Taking these measures, we can get a quick picture of the pollution situation and further make better strategies for improving IAQ. Site-specific strategies for different school locations, such as transportation areas and industrial areas, should be developed to suit the characteristics of the schools in different areas.

4. Roadmap for the future improvement of classroom air quality

4.1. Raising awareness

4.1.1. Deepening occupants' understanding of IAQ

Occupant behavior is one of the factors affecting CAQ. Therefore, there is a need to encourage and train school occupants (mostly teachers and children) [281,282]. Scientific activities and seminars are necessary to improve the occupants' knowledge and perception regarding the importance of indoor air quality [283]. To identify current problems and raise the solutions to solve these problems, children are asked to conceptualize solution. It is found that children can be valuable contributors in co-designing classroom environments [284]. By comparing the test-retest repeatability of questionnaires filled by children and parents, it can be concluded that children can give as, or even more, repeatable information about their respiratory symptoms and perceived indoor air quality than their parents [285]. Therefore, it may be possible to learn more about the needs of children and their ideas for improving indoor air quality.

4.1.2. Deepening the understanding of pollutants characteristics

Compared with single pollutant measurements, multiple pollutants are more frequently studied. Most of these studies are focused on particulate matter, CO_2, VOCs, and bioaerosols. However, the sample size for many measurements is not large. Most of the measurements are conducted for less than one year. Therefore, further research is needed to analyze the pollutant characteristics in school buildings in the world's different climatic, social, and cultural regions [286]. Long-term measures are essential for clarifying the hazards of contaminants. Simultaneous effects of different local factors add complexity, and more studies during different seasons are needed to identify additional developments in the future [287]. For other types of pollutants, more in-depth research is required in order to understand the specific mechanism of the impact on CAQ. Future research should aim at *in situ* measurements and a source apportionment approach to investigate CAQ levels within educational buildings to secure healthy conditions for the pupils and staff.

For some pollutants, like the airborne particles, experimental investigation of the indoor school environment is often difficult and expensive and poses several logistical and practical difficulties. Thus, it cannot be done frequently; additionally, air quality measurement to clarify uncertainties during early design stages is not possible. Physical processed are needed to address these situations. Numerical investigation is a great alternative in complementing laboratory and on-site measurements. Alternatively, numerical simulations based on the computational fluid dynamics (CFD) technique can be a powerful tool to compliment measurement studies and provide valuable information regarding influential parameters in assessing CAQ [159,161]. In the future, more parameters and specific data should be obtained for CFD analysis to get a more in-depth understanding at contaminant characteristics.

4.1.3. Deepening the understanding of health and performance effects

Many studies have focused on health and performance effects. Studies on social, economic, and multiple/synergic impacts are lacking. The main research hotspots are academic achievement performance and health effects associated with respiratory symptoms. Extending the analysis to other buildings such as homes seems necessary to determine children's exposure to indoor air with more accuracy and to assess their lifetime health risks [288]. A cross-sectional study is a commonly used method to investigate the relationship between health impacts and indoor pollutants. A longitudinal study would help increase the robustness of the quantitative analysis of the effects of the duration of pollutant exposures on health symptoms [289]. In addition, toxicological evaluations are recommended to develop practical risk assessments in future research [25]. More in-depth analysis of contaminants, such as characterizing particles' chemical composition, is needed to assess toxicology and health impacts [290]. It would also be helpful to examine how indoor environment quality in homes influences children's sleep quality and, consequently, whether it affects the next day's performance in schools and learning. Light exposure in schools and stress caused by exposures in classrooms may result in sleep disturbance of pupils and consequently poor cognitive performance and learning. It would be useful to examine these issues as well. Finally, the socio-economic consequences of health and performance effects on children in classrooms should be considered, including also the impact on teachers. Children staying at home because of health problems generate absenteeism from parents and guardians. Poor learning may have consequences on future incomes and thus may have consequences for individuals and society.

4.2. Source control

4.2.1. Outdoor environment

The primary source of PM contamination in schools is outdoor air, like traffic and industrial emission [112]. The main source of CO and NO_2 is traffic. Infiltration from outdoor air strongly influences indoor levels, in particular within short distance from roadways or high-density industrial or traffic areas. Studies have shown that numerous schools are located in areas with high levels of air pollutants [133,259,260]. The school's geographical location plays a significant role in formulating its indoor and direct outdoor air quality. PM10 and total bacteria count levels for schools surrounded by roadways were found to be significantly lower than surrounded by buildings and mountains [291]. Therefore, suitable management for school building characteristics is needed. For new schools, reasonable consideration needs to be given to the location of the school, and for existing schools, pollutant-free control is required based on the environmental characteristics of the school's surroundings.

4.2.2. Indoor material and activity

VOC exposure in schools is often related to construction materials, furnishings and painting materials, etc. Some of these emissions can be prevented by using low-emitting materials like improved plastics and paints (phenol resins instead of urea resins, polyurethane coatings, etc.) and solid wood or old furniture [291]. In addition, sealing and storing the liquid materials (paints, adhesives, cleaning products,etc.) and minimizing storage periods can mitigate pollution to some extent [292]. Pupil activities is an important source of particle resuspension. Vacuum cleaning has a significant effect on reducing resuspension of small and larger particles, 2.5–10 μm particles [293].

4.3. Mitigation measures

The use of natural ventilation provides acceptable IAQ levels and reduces energy use given the consequent reduction in the use of mechanical ventilation [278]; therefore, most of the schools choose natural ventilation as the primary method for improving IAQ. However, indoor air levels were affected by surrounding environments [294,295] and improper natural ventilation practices may deteriorate indoor air quality; thus, it is essential to develop mitigation strategies to improve the IAQ and prevent the transmission of infectious disease in a naturally ventilated classroom [140]. For example, the proper design of the window openings, the interior layout, and the fresh air intakes are important to the IAQ of existing buildings adjacent to roadways [295]. However, the potential capacity of natural ventilation can be reduced by up to 88% considering WHO thresholds for $PM_{2.5}$ according to a case study in Chongqing, China [279].

Relying on window opening as a tool for ventilation in heavily polluted areas is challenging because increased ventilation decreases the indoor CO_2 levels but increases the NO_2 and SO_2 levels [296]. Hence proper management for school building characteristics is needed. Thus, it is essential to develop practical tools for detecting pollutant concentrations using the limited information available from public sources [280]. Taking these measures, we can get a quick picture of the pollution situation allowing better strategies for improving CAQ to be devised.

Field measurement, as well as numerical evaluation of CAQ, are the two methods frequently used to evaluate ventilation effectiveness. Good quality ventilation measurements are essential to produce accurate results. In many studies, the measurement approaches, boundary and climate conditions, and the statistical analysis of data collected were not described in adequate detail to evaluate their quality, reliability, validity, replicability, or applicability to the study design. For example, the airtightness of the school building needs to be considered when evaluating the effect of natural ventilation [297]. The outdoor environment is an inescapable factor affecting indoor air quality. In the future, site-specific strategies for different school locations, such as proximity to transportation routes and industrial areas, should be developed to suit the characteristics of schools in different regions. The research findings and recommendations could thus apply to many other schools with the same features.

4.4. Integrated control

4.4.1. Building design for balancing energy efficiency and human perceptions

The building itself is one of the main factors in improving IAQ. Optimizing passive design parameters of buildings (e.g., window to wall ratios, window orientations and sun shading installations) can significantly reduce the ventilation demands while maintaining indoor thermal comfort [44]. Airtight buildings that have been designed to conserve energy also reduce the infiltration of outside air. There is a nexus between ventilation and indoor air quality in buildings [277] since, while airtight buildings can help conserve energy, they can accumulate pollutants inside. However, when individuals stay indoors for long periods, they will be at risk of adverse health effects through their exposure to a potentially polluted indoor environment over a sustained period [298]. While studies are available around transport microenvironments [299], similar research is needed for school classrooms to fill this existing gap in current understanding.

4.4.2. Choice of ventilation strategy

Different ventilation strategies have different performance in terms of improving IAQ, as well as energy saving performance. The use of sustainable design, such as solar energy, can improve energy efficiency while ensuring thermal comfort. Solar air heating technology is combined into the ventilation system. The average value of hourly solar contributions can be as high as 34.3% over a heating season. Although the economic effect of the new system is not the best, both its energy saving effect and environmental protection effect are significant [300]. Some ventilation systems are complex, such as passive with heat recovery. The feasibility of the system and the effectiveness needs to be taken into account. The assessment of the ventilation performance of PVHR systems depending solely on wind and buoyancy is complicated as they are dynamic systems that constantly balancing with the surrounding conditions, and the operation is highly correlated to the airtightness of the building's envelope [24]. It is necessary to develop more efficient and energy-saving systems in the future.

Besides, a solid and quantifiable comparison between the low-cost mitigation measures to enhance the air quality is recommended to clarify the economic and practical implementation and the effects on energy sustainability, thermal comfort, health, and security of the occupants [301]. For the future, the application of more expensive and complex mitigation measures should be evaluated.

5. Conclusions

This article presents a comprehensive review of the last 50 years of classroom air quality research to examine, discuss and understand the interaction between classroom air quality and pupils' performance, comfort, and health. The published articles summarized here investigated schools' air quality in 40 countries worldwide.

Most schools worldwide have basic natural ventilation systems; however, inefficient performance is inadequate for meeting the needs of their users. The design of new schools should require a particular type of effective ventilation system for achieving good air quality and protection against exposure to airborne particles and VOCs. When refurbishing existing schools, the challenge comes from finding a feasible solution to meet the CAQ requirements given the existing infrastructure. Demand-controlled ventilation, combined with an efficient air distribution system, could reduce the energy use required for mechanical ventilation and trigger the biggest saving whilst securing the health and well-being of children in schools.

Probably the only general conclusion from the extant literature on thermal comfort is that school pupils tend to feel comfortable in indoor climates that are generally cooler than environments (e.g. offices) where adults feel thermally neutral. The classroom temperature that pupils deem comfortable depends on many factors, including, amongst others, the climatic context of the pupils and their prior exposure to air conditioning. More studies on the direct associations between indoor classroom thermal conditions and pupil performance are needed to confirm the suitable temperature-performance model.

In terms of pupils' learning performance, earlier studies consistently show that reduced classroom air quality will cause a reduction in cognitive performance of pupils with resulting negative consequences for progressive learning whilst increasing short-term sick leave. Most of the published work relates to the performance of school work, with the measurements of CO_2 concentrations being the proxy for classroom ventilation and air quality. Little data exists regarding the effects of specific pollutants, and such studies are much needed. The existing evidence suggests that keeping classroom CO_2 levels below 900 ppm (absolute level) reduces the negative impact on learning, but even lower levels may be more conducive; however, data for lower CO_2 levels are scarce. Children also prefer a cooler environment for effective learning.

Exposure to various air pollutants in school buildings risks severe damage to pupils' health since they inhale a larger volume of air corresponding to their body weights than do adults. This is especially important as many studies reported higher pollutant concentrations in schools than in residential and commercial buildings. The VOC pollutants are among the leading indoor air pollutants causing severe health issues for children and adults. On the other hand, many schools have identified particulate matter pollution as a major source of indoor air pollution. In addition, *Penicillium, Cladosporium, Aspergillus,* and *Alternaria* were the most common fungi found in school indoor environments, and their prevalence varies depending on climate and location, whether rural or urban.

Worldwide energy consumption is continually growing, and a large proportion of this growth is associated with non-domestic buildings. While few research studies provide a breakdown of energy consumption by energy category, including thermal energy and electrical energy, there is limited insight demonstrating detailed energy use profiles for heating, ventilation, and other building service systems in school buildings.

There is a great need for more comprehensive studies with larger sample sizes, including prospective cohort studies, with a characterization of strategies to promote indoor school environmental quality on environmental health exposure, student health and wellness outcomes, indoor satisfaction, and cognitive performance. Both ecological and behavioral factors affecting classroom air quality should be characterized along with the effects of indoor environmental controls on energy consumption.

Author Statement

Sasan Sadrizadeh: Coordination, paper structure, writing, reviewing, and revising. Other authors: writing, reviewing, and editing.

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.

Acknowledgment

This literature review study is inspired by the UK Clean Air Programme TAPAS-Tackling air pollution at school (NE/V002341/1). The authors from the Joint International Research Laboratory of Green Buildings and Built Environments would like to thank the sponsors for the research project "School Building and Children's Health" [Grant No: B13041]. This research study was financially supported by Formas, the Swedish research council [Grant No: 2021-01422]. The authors are also grateful for the input from Sustainable Energy & Environmental Systems Department at Lawrence Berkeley National Laboratory.

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