Selected issues of indoor environment conditions in polish educational buildings in the light of current regulations and recommendations

Wybrane zagadnienia warunków środowiska wewnętrznego w polskich budynkach edukacyjnych w świetle obowiązujących przepisów i zaleceń

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Ensuring optimal thermal comfort conditions and air quality in educational buildings is crucial for students and teachers' health. Appropriate indoor environment not only contributes to good physical well-being but also impacts the effectiveness of the teaching process, supporting focused learning. Also, systematic control and monitoring of the levels of microbiological air pollutants, along with the identification of their emission sources, constitute the foundation of an effective strategy to improve indoor air quality (IAQ). Efficient management of these parameters contributes not only to health protection but also to increased comfort during both learning and work. The presented paper is of a review nature. Its aim was to develop a comprehensive study related to shaping optimal thermal and humidity conditions and ensuring proper IAQ, including microbiological IAQ, in educational buildings. The authors reviewed various uninform legal regulations and recommendations (both Polish and international) regarding thermal comfort parameters and IAQ. Different measurement and assessment methods of these conditions were described, including examples of measurement equipment. Finally, ways in which indoor environment can be shaped using energy-efficient heating, ventilation and air-conditioning (HVAC) system solutions in such facilities were presented. The paper can provide assistance in designing new educational buildings or retrofitting existing ones, as well as improving indoor environment management systems. It can inspire investments in modern HVAC systems, as well as promote the use of renewable energy sources. Furthermore, it might be a source of knowledge to raise awareness regarding the impact of indoor environment conditions on health and learning efficiency.
Keywords: educational buildings; school; preschool; thermal comfort; indoor air quality (IAQ); harmful biological agents (HBAs); bioaerosol; HVAC systems; renewable energy sources

Zapewnienie optymalnych warunków komfortu termicznego i jakości powietrza w budynkach edukacyjnych jest kluczowe dla zdrowia uczniów i nauczycieli. Odpowiednie warunki środowiska wewnętrznego nie tylko przyczyniają się do dobrego samopoczucia fizycznego, ale także wpływają na skuteczność procesu nauczania, wspierając koncentrację podczas nauki. Również systematyczna kontrola i monitorowanie poziomów mikrobiologicznych zanieczyszczeń powietrza, wraz z identyfikacją ich źródeł emisji, stanowią fundament skutecznej strategii poprawy jakości powietrza wewnątrz pomieszczeń. Efektywne zarządzanie tymi parametrami przyczynia się nie tylko do ochrony zdrowia, ale także do zwiększenia komfortu zarówno podczas nauki, jak i pracy. Zaprezentowany artykuł ma charakter przeglądowy. Jego celem było przygotowanie kompleksowego opracowania dotyczącego kształtowania optymalnych warunków cieplnych i wilgotnościowych oraz zapewnienia odpowiedniej jakości powietrza w budynkach edukacyjnych, uwzględniając także mikrobiologiczną jakość powietrza. Autorzy omówili różne niejednolite przepisy prawne i zalecenia (zarówno polskie, jak i międzynarodowe) dotyczące parametrów komfortu termicznego i jakości środowiska wewnętrznego. Opisano metody pomiaru i oceny tych warunków, wraz z przykładami sprzętu pomiarowego. Przedstawiono sposoby kształtowania środowiska wewnętrznego za pomocą energooszczędnych rozwiązań systemów ogrzewania, wentylacji i klimatyzacji (HVAC) w takich obiektach. Artykuł może być pomocny przy projektowaniu nowych budynków edukacyjnych lub modernizacji istniejących, a także przy poprawie funkcjonowania systemów zarządzania środowiskiem wewnętrznym. Może stanowić źródło inspiracji do inwestowania w nowoczesne systemy HVAC oraz promować wykorzystanie odnawialnych źródeł energii. Ponadto, może być źródłem wiedzy zwiększającej świadomość na temat wpływu warunków środowiska wewnętrznego na zdrowie i efektywność nauki.
Słowa kluczowe: budynki edukacyjne; szkoły; przedszkola; komfort cieplny; jakość powietrza wewnętrznego; szkodliwe czynniki biologiczne (SCB); bioaerozol; systemy HVAC; odnawialne źródła energii

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Introduction

The scope of the problem

Educational buildings are a key foundation for the development of society and individuals. They are not only physical spaces of learning, but also places where the future of society is shaped, culture and innovation are developed, and social bounds are strengthened. They are the foundation upon which social progress and individual development are based. In the 2022/23 school year, in Poland 36,751 pre-primary, primary and post-primary educational establishments operated in which 5.1 million children, youth and adults were enrolled, accounting for 13.6% of the country's population [1]. They were supplemented by 359 higher education institutions which were attended by 1,223.6 thousand students [1]. In the European Union there were 93.3 million pupils and students enrolled, accounting for 21% of the total European Union population [2]. In Poland, on average about 200 new educational buildings are built every year and the same number is expanded [3]. The share of Polish people aged 25-64 who have completed at least secondary education amounted to 93.5% in 2022, compared to an average of 79.5% for the European Union [4]. It can be estimated that students in Poland and the European Union spend on average about 18,720 hours in educational buildings throughout their school and academic education. These figures highlight how much time a significant proportion of the population spends in buildings during their education, which makes it crucial to provide the school community with an indoor environment that supports health and well-being.

In accordance with the regulations of the Minister of National Education and Sport of December 31, 2002 (as amended) regarding safety and hygiene in public and non-public schools and facilities, school principals are obliged to ensure safe and hygienic conditions for both students and teachers [5]. This is supported by the school framework statutes and other general regulations concerning occupational safety and hygiene.

With the progressing process of urbanisation, the increasing number of students, and the growing complexity of educational requirements, educational buildings must meet the challenges related to maintaining optimal thermal comfort conditions. At the same time, in the age of growing ecological awareness, issues related to indoor air quality (IAQ) are becoming particularly important, affecting both the health of students and teachers and the effectiveness of the teaching process. With a focus on sustainable development, educational buildings are designed with consideration for energy efficiency. This includes, among others, the use of energy-efficient heating, ventilation and air conditioning (HVAC) systems and the use of renewable energy sources.

The issue of indoor air conditions along with examples of research results

Thermal comfort in classrooms (fig. 1), as well as in other places, depends on the basic indoor air parameters such as temperature, humidity, velocity and other parameters like metabolic rate and clothing insulation, although students' activity and clothing thermal insulation do not change widely in classrooms. Generally, thermal comfort factors are important for health, well-being, and productivity of occupants. Moreover, poor IAQ can directly affect physical health and learning performance. Especially, high carbon dioxide level is the main reason for low air quality in such places. The main source of CO_2 in school facilities is usually the air exhaled by individuals. The level of CO_2 in classrooms is influenced by various factors such as:

- the occupancy rate of the room,
- the level of activity among occupants,
- the amount of time occupants spend in the room,
- the ventilation rate [6].

The school's ventilation system allows the staff to control the indoor conditions, maintain a comfortable thermal environment and limit the CO_2 level in all educational spaces. Classrooms in educational buildings, such as schools and universities, are often not adequately ventilated. Due to that pupils and students are not provided with optimal air quality and thermal comfort conditions.

Examples of research on thermal comfort conditions and air quality in educational buildings can be found in the literature. Their results indicate poor air quality [7-11], insufficient values of ventilation air volume flow rate [12] and lack of thermal comfort conditions, e.g. due to overheating of classrooms [13, 14] in schools. The pupils themselves also point out the poor quality of the indoor environment [15]. It was proved that the indoor environment affects not only the thermal comfort, but also the health of students [16] and their academic achievements [17]. The research [18] indicated that an increase in air temperature in the classroom negatively affected educational outcomes. Increasing the indoor air temperature from 20°C to 30°C resulted in a 20% decrease in the effectiveness of school obligations. Another research [19] indicated significant variability in indoor air parameters associated with regular windows' opening between lessons. It was pointed out that achieving appropriate thermal comfort parameters can be a challenge especially in classrooms with significant internal gains from computer equipment [20]. Proper design of the ventilation system is key to avoid thermal discomfort. Various solutions of classroom ventilation systems and devices can be applied for this purpose [21-24].

In the paper [25], the authors conducted research on thermal comfort and air quality conditions in a university computer laboratory with a volume of 97 m^3 equipped with 9 computer workstations for a maximum of 17 occupants. The room was ventilated using natural ventilation – the air was supplied by infiltration and leaks through the windows and the external building partition and exhausted through the ventilation grille in the upper part of the room. The research encompassed long-term measurements of indoor air temperature and relative humidity as well as CO_2 level over the period of two months from October to December at 6 measurement points in the laboratory. Short-term measurements of thermal comfort conditions, including indoor air velocity, temperature and relative humidity as well as PMV and PPD indices, during classes in the presence of occupants were also carried out. The research was complemented by a survey among the students and staff assessing their thermal and humidity perceptions. The results of measurements and survey indicated that the laboratory's air temperature was too high, leading to a sensation of heat among occupants; the air humidity was too low, perceived as dry by occupants; adequate air

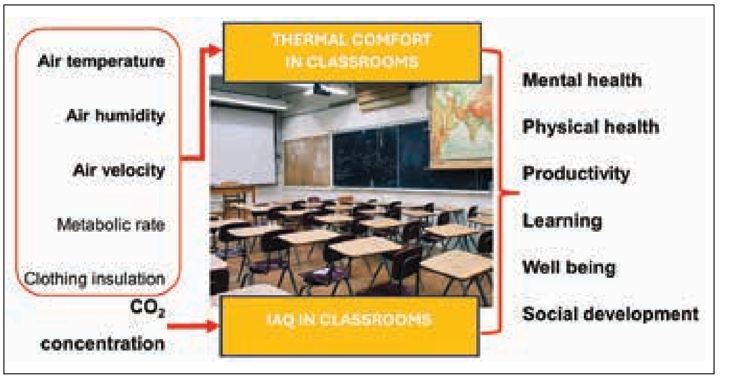

Fig. 1. IAQ and basic thermal comfort factors in classrooms and their effects

velocity value was not ensured, resulting in air stagnation; the maximum CO_2 level exceeded the recommended value by over 200%. The thermal comfort conditions in the room were only periodically optimal, but not sustained over longer periods. The unfavourable thermal and humidity conditions and IAQ were attributed to ineffective natural ventilation, which failed to provide the necessary value of supply air volume flow rate. Periodic ventilation of the room by opening windows between sessions only temporarily and briefly improved indoor air conditions. It was indicated that to ensure thermal comfort conditions and adequate air quality, it is essential to implement a properly designed ventilation system that will ensure the required air exchange rate in the room.

Inadequate ventilation, as well as poor IAQ in educational facilities, can lead to periodic absenteeism, health problems for both students and teachers, and a decrease in overall learning and working comfort. Yet, a frequently overlooked issue in assessing people's exposure to indoor air pollutants is the threat posed by harmful biological agents (HBAs). These factors pose the most common threat, being transported through the air as bioaerosols. The term "bioaerosol" refers to a two-phase system consisting of suspended biological particles in the air, such as bacteria, microscopic fungi, or viruses [26].

Airborne bioaerosols can trigger a variety of diseases, such as pneumonia or tuberculosis caused by bacteria entering the respiratory system. Bacteria and microfungi can contribute to asthma, hay fever, bronchitis, sinusitis, and conjunctivitis. Metabolites of some non-pathogenic bacteria can also pose health risks. Particularly concerning are Gram-negative bacteria due to endotoxin, a component of their cell wall [26-28].

The results of air analyses carried out in educational buildings unequivocally point to the necessity of continuous monitoring of the microbiological IAQ in such facilities [29-33]. For example, from 2019 to 2022, research was carried out on the quantitative and qualitative analysis of biological aerosols isolated from the air in preschool classrooms located in Gliwice, Poland (Upper Silesia) (fig. 2).

During the research, samples were collected using a 6-stage Andersen impactor with cut-off diameters of 7.0, 4.7, 3.3, 2.1, 1.1, and 0.65 µm (Thermo Fisher Scientific, Waltham, MA, USA) from the breathing zone of children, approximately 1 m above the floor level. Determining the aerodynamic diameter ranges in which biological particles were present in the air in the analysed educational facility (known as the particle size distribution) allowed estimating which fractions of biological aerosols were deposited in specific segments of children's respiratory systems (fig. 3). The concentrations of bioaerosols were expressed as the number of Colony Forming Units per cubic meter (CFU/m³).

Fig. 2.
The preschool classroom during measurements

$d_{ae} > 7.0$ µm	•do not penetrate deep into the respiratory system
$7.0 \geq d_{ae} > 4.7$ µm	•reach the throat
$4.7 \geq d_{ae} > 3.3$ µm	•reach the trachea and primary bronchi
$3.3 \geq d_{ae} > 2.1$ µm	•reach the secondary bronchi
$2.1 \geq d_{ae} > 1.1$ µm	•reach the terminal bronchioles
$1.1 \geq d_{ae} > 0.65$ µm	•reach the pulmonary bronchioles

Fig. 3.
Relationship between the aerodynamic diameter (d_{ae}) of particles travelling in the respiratory airflow and their maximum depth of penetration in the respiratory tract

In the analysed preschool classrooms, a particularly high proportion of bacterial particles with aerodynamic diameters in the range of 0.65 µm to 3.3 µm was observed. It is crucial to emphasize that the respirable fraction (particles with an aerodynamic diameter ≤ 3.3 µm) can pose a significant health concern as it can penetrate deep into the respiratory system when inhaled. For fungal aerosol, a high concentration of fungal particles with aerodynamic diameters in the range of 3.3 µm to 4.7 µm was observed, indicating that the fungal aerosol in the indoor air of the analysed preschool mainly existed in the form of fungal and dust aggregates. Particles in this size range can be deposited in the trachea region and induce asthmatic reactions.

Microorganisms collected from the air in preschool classrooms were also subjected to species identification using the BIOLOG system (Harward, California, USA), which constituted another stage of the research. In the qualitative analysis, microplates GEN III were used for bacteria, and FF microplates were used for microfungi.

The predominant bacterial species isolated from the air in the discussed preschool classrooms belonged to Gram-positive cocci, specifically: *Staphylococcus aureus*, *Staphylococcus lentus*, *Micrococcus luteus D* and *Macrococcus equipercicus*. The main source of emission for this group of bacteria is the human body (respiratory system, human skin), which is the most likely cause of the significant quantitative prevalence of these bacteria over other components of the air microflora. Based on the qualitative analysis of the fungal aerosol, it was found that the predominant fungi in the preschool classrooms were: *Penicillium*, *Aspergillus*, and *Cladosporium*. During the research, species such as *Aspergillus flavus* were isolated, which can have adverse health effects on children and preschool staff with reduced immunity. It is worth emphasizing that even low doses of aflatoxins produced by *Aspergillus flavus* can cause chronic aflatoxicosis when inhaled daily, leading to immune suppression among occupants of preschool facilities.

The aim of the paper

The importance of indoor environmental conditions in buildings is no longer questioned nowadays. The issue of maintaining indoor environment conditions in schools and universities is increasingly addressed in the literature, both in research and within the scope of applicable regulations (e.g., in compendia [34, 35]). Currently, there is a lack of uniform legal regulations and guidelines regarding indoor environment conditions and air quality in educational buildings, which is essential for both designers and managers of these buildings. Due to engineering legislative changes, engineers are obligated to continuously update information in the legal aspect as well as review the current state of knowledge in the literature and analyse information on possible technical solutions in terms of energy efficiency.

The presented paper is of a review nature. Its aim was to develop a comprehensive study containing practical information regarding educational buildings in the context of:

- ☐ legal regulations and recommendations (both Polish and international) concerning thermal comfort conditions and IAQ,

- measurement methods of indoor environment conditions, including the microbiological quality of air,
- possibilities for improving thermal comfort conditions and indoor air quality, as well as increasing the energy efficiency of the building through the HVAC system's retrofitting.

Criteria and methods for assessing indoor environment conditions in educational buildings

Thermal and humidity conditions, thermal comfort and IAQ

Thermal and humidity conditions

There are no clear guidelines in the literature regarding the design parameters of indoor air for educational buildings, taking into account their specificity. As for thermal and humidity conditions, the PN-78/B-03421 standard [36], referenced by the Polish Technical Conditions [37], is applicable in design. The design parameters for indoor air in rooms intended for continuous human occupancy with a low metabolic rate (corresponding to learning) are as follows: the indoor air temperature in winter should be 20-22ºC, in summer: 23-26ºC, relative humidity in winter: 40-60%, in summer: 40-55% [36, 38].

The basic Polish requirements regarding occupational safety and hygiene in schools are specified in the regulation dated December 31, 2002 (Journal of Laws of 2003, No. 6, item 69, as amended) concerning occupational safety and hygiene in public and non-public schools and establishments [39]. Regarding thermal conditions, paragraph 17 of this regulation states the following requirement: "*in rooms where classes are conducted, a temperature of at least 18°C must be maintained.*" If it is not possible to maintain such a temperature, the school head teacher suspends classes for a specified period, notifying the governing body about this decision. The standard [40] specifies that this value should be greater than 20°C.

In addition to complying with the requirements specified in standards and regulations, it is important to pay attention to recommendations and criteria provided in foreign sources directly related to educational buildings/rooms. An example is the Building Bulletin 101 "Guidelines on ventilation, thermal comfort and indoor air quality in schools" [6]. According to it, "*recommended operative temperature during the heating season for spaces with a normal level of activity, including teaching, study, exams, admin and staff areas, prep rooms, practical spaces, and computer suites, should be equal to 20°C (maximum 25°C, at maximum occupancy).*" According to ISHRAE [41] this value should be 22°C±3°C. Similar requirements regarding operative temperature according to another source will be cited later in the paper.

Thermal comfort

Thermal comfort expresses the satisfaction of an individual (or a group of individuals) with the thermal conditions of the indoor environment they occupy [42]. The fundamental international standards regarding thermal comfort are PN-EN ISO 7730:2006 [43] and ANSI/ASHRAE Standard 55 [44]. These standards use the PMV (Predictive Mean Vote) and PPD (Predicted Percentage of Dissatisfied) indices proposed by P.O. Fanger to assess thermal balance.

The PMV-PPD model is based on American and European experiments conducted in a well-controlled environment [45]. It assumes the stability or slight fluctuations of thermal conditions in the room without taking into account the phenomenon of human acclimatisation. Therefore, this model is applicable to spaces with mechanical ventilation or air conditioning, rather than natural ventilation.

Most of the existing educational buildings in Poland (>99% [35]) are ventilated in a natural way (utilising gravity ventilation). Indoor air parameters depend on outdoor conditions and the operation of the central heating system during the winter season [38].

The appropriate model for spaces with natural ventilation is the adaptive model mentioned in the American standard [44] and the European standard in Polish translation [40], which replaced the previously functioning European standard [46] several years ago. An adaptive model establishes a connection between indoor air design temperatures or acceptable temperature ranges and outdoor meteorological or climatological factors. It indicates the range of optimal operative temperature for a given category of rooms I-III (fig. 4), where category I represents the highest requirements for buildings where individuals with special needs will be present, category II is the standard for new buildings, whereas for the retrofitted buildings category I, II, or III can be applied [40].

Children, especially young ones, should be classified as occupants of the highest category I according to [40]. This means that the thermal environment conditions in educational spaces should be under strict control, and fluctuations in indoor air parameters should be minimal [38].

According to the standard PN-EN 16798-1:2019-06, the design requirements for the operative temperature in office spaces, including classrooms, with mechanical cooling (and heating) systems are as follows: a minimum of 21°C (heating season) and a maximum of 25.5°C (cooling season) for category I indoor environment. The thermal comfort indices for category I are PMV = – 0.2-0.2, PPD <6% [44, 46].

The standard [40] recommends, similar to the ASHRAE 55 standard [44], that the air specific humidity should not exceed 12 g/kg. Regulations also provide recommendations regarding relative humidity for air dehumidification and humidification. However, standard [40] indicates that in spaces intended for human occupancy without additional humidity requirements (e.g. offices, schools, and residential buildings), these additional processes are usually not necessary, unlike in museums or specific healthcare facilities. Recommendations regarding air relative humidity values are varied. According to [40], this value should be 60%, while according to [41], it should range from 30% to 70% depending on the season.

In addition to air temperature and humidity, another parameter affecting thermal comfort is air velocity, which according to [36] should be a maximum of 0.2 m/s in winter and 0.3 m/s in summer. According to [40], for category I, air velocity should be a maximum of 0.1 m/s in the heating season and 0.12 m/s in the cooling season. According to [6, 41] this value should be lower than 0.2 m/s. Regulations regarding thermal comfort introduce the draught risk (DR) index which should be <10% for category I [43].

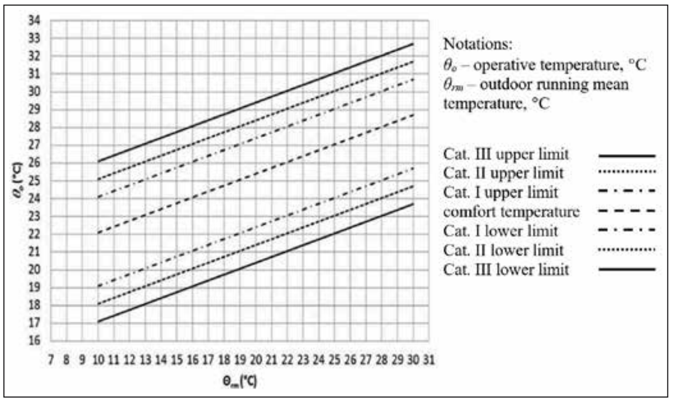

Fig. 4. Recommended operative temperature values for buildings without a mechanical cooling system, provided in the European standard [40]

It should be noted that children usually perceive the environment as warmer than adults [47], so it is advisable to adhere more closely to indoor air requirements in schools. However, the mentioned standards have only a discretionary character [38]. Moreover, the literature also states that the presented thermal comfort models (PMV-PPD and adaptive) are not applicable among children. Guidelines based on experiments involving adults, rather than children, may not be considered suitable for assessing the thermal comfort of children [48]. Nevertheless, they are still applicable to older occupants of university facilities and adult schools.

Indoor Air Quality (IAQ)

The most commonly used indicator of IAQ is the CO_2 level. There are no comprehensive legally binding regulations regarding the qualitative requirements for indoor air. The default design CO_2 level exceeding the outdoor level according to PN-EN 16798-1:2019-06 [40] for unadapted individuals, is 800 ppm (category I), assuming a standard CO_2 emission rate of 20 l/(h per person). According to [41] the design CO_2 level exceeding the outdoor level should be 500 ppm.

The most commonly reported in literature limit value of CO_2 level is 1000 ppm. This is known as the Pettenkofer number (named after the researcher who observed the correlation between CO_2 level and human performance). This value is also recommended by ASHRAE [49], ISIAQ [50] and Danish regulations [51]. Higher values are provided, for example, by the German standard DIN 1946-Teil 2, which considers 1500 ppm as the momentary maximum value for CO_2 level in terms of hygiene [52].

Based on foreign literature sources and the previously mentioned design guidelines Building Bulletin 101 [6] it can be stated that the maximum CO_2 level should be assumed at 1500 ppm for mechanical ventilation and 2000 ppm for natural ventilation for a period not exceeding 20 minutes when the number of occupants in the room is equal to or less than the design occupancy.

Methods for assessing indoor environment conditions

Comprehensive assessment of indoor environment conditions is essential for making retrofitting and modernisation decisions in buildings, including educational facilities. The goal is to improve both thermal and humidity conditions as well as IAQ and thermal comfort to recommended levels as discussed earlier in the paper.

A comprehensive assessment of indoor (thermal) environment conditions includes measurements of basic air parameters: temperature, mean radiant temperature, humidity, and velocity [53]. These measurements should be carried out in the occupants' zone, defined as the space enclosed from above by an imaginary plane at a height of 1.8 m and planes located 1 m away from the external walls [44]. Generally, measurements should be taken at three heights: head, torso, and feet, adjusting heights to human body position (standing, sitting) according to the standard [43] and ASHRAE 55 [44]. In educational buildings the sitting position is predominant.

Considering IAQ in the diagnostic measurements of educational buildings, the highest CO_2 level is observed in the areas where students are present and at their learning stations. According to the Building Bulletin 101 guidelines [6], "*CO_2 levels should be measured at seated head height in all teaching and learning spaces*". In practice, it is also recommended to conduct measurements of CO_2 levels in the area where air is supplied and removed from the room, as well as inside the room at a height of about 1 meter. It is not recommended to measure CO_2 levels in the corners of rooms or in the immediate vicinity of windows and doors.

The proper selection of measurement devices tailored to the specific indoor environment is a crucial aspect. Due to generally low air velocity values in spaces occupied by people, including classrooms, and significant fluctuations of this value, it is appropriate to use multi-directional anemometers [53]. The measurement instruments should meet normative requirements in terms of accuracy, measurement range, and device response time [54].

It should be noted that measured thermal parameters alone are not sufficient for assessing the indoor environment's acceptability by occupants. This is because only the combination of these parameters determines people's thermal sensations. Therefore, indicators such as operative temperature, the PMV-PPD model, and the draught risk (DR) model or adaptive model are applied. However, all developed models are based on statistical analyses of thermal sensations in large groups of people. In practice this means that predicting the sensations of a specific individual is not possible; only the most probable sensations can be determined [53]. The perception of thermal comfort is an individual matter, so survey research is often used. Examples of surveys can be found in the literature, e.g. in [55].

The diagnostic measurement of indoor environmental conditions in educational buildings encompasses a variety of measurement methods. A description of in-situ indoor environmental diagnostics can be found in the literature, e.g. in Volume 4 of the guidebook for thermal diagnostics of buildings [56].

As mentioned earlier, air velocity is recommended to be measured using multi-directional anemometers, which allow for precise measurement of instantaneous and average air velocity in a range from, e.g. 0.05 m/s with an accuracy of ±0.02 m/s ±1.5%. These devices are used in thermal comfort research. Thermal comfort can be comprehensively measured using a microclimate meter. This device consists of measurement modules (Fig. 5), integrated with probes for measuring air velocity, globe temperature, air temperature, natural wet bulb temperature, relative humidity, and barometric pressure. The measurement modules are mounted on a tripod at appropriate levels. The kit also includes a recording module and a radio receiver, allowing measurements to be taken without interference.

The assessment of air volume flow rate in the installation can be carried out, e.g. by using a balometer (Fig. 5). The measurement involves placing the device at the air supply grille so that the upper edge of the measurement hood touches the edge of the grille. Multipoint measurement of pressure difference (static and total) takes place in the measurement grid connected to a micromanometer at all measurement points simultaneously. Furthermore, determining the number of ventilation air exchanges in a building with natural ventilation is possible based on specialised measurements or calculations using computer software for simulating airflow through buildings (CONTAM, ESP-r, and CFD-based). The air exchange rate can be

Fig. 5.
Measurement module for thermal comfort research (on the left) and balometer for air volume flow rate measurement (on the right)

determined using the tracer gas method, in which CO_2 concentration profiles are recorded to determine the number of air exchanges using the metabolic carbon dioxide decay method. A description of this measurement method can be found in the literature, e.g. in Volume 3 of the guidebook for thermal diagnostics of buildings [57].

Carbon dioxide, the main parameter for assessing indoor air quality, can be determined using portable CO_2 meters or specialised transducers that operate based on infrared technology. More information can be found in the literature, e.g. in the bulletin [58].

Microbiological IAQ

The legal framework

Introducing comprehensive guidelines for assessing human exposure to air pollution, particularly regarding HBAs, remains a persistently overlooked challenge, especially within educational buildings. In the European Union, issues concerning protection of workers' health against the effects of exposure to HBAs are regulated by Directive 2000/54/EC of the European Parliament dated from 8 September 2000 [59]. In Poland, the basic document implementing the provisions of this directive is the Regulation of the Minister of Health of 22 April, 2005 on biological agents harmful to health in the work environment and the protection of health of workers professionally exposed to those agents (Journal of Laws, 2005, no 81, item 716 as amended: Journal of Laws, 2020, item 2234), according to which the following are recognised as HBAs: „cellular microorganisms, internal parasites, non-cellular entities capable of replication or transferring genetic material, including genetically modified cell cultures, which may be the cause of infection, allergy or poisoning" [60].

However, it should be emphasized that none of the above-mentioned documents defines the criteria and standards for concentration limits of HBAs. For several years, in Poland there have been only proposed limit values of concentrations of microorganisms and bacterial endotoxin in indoor air, which can be helpful in assessing the exposure to HBAs in the work environment. These recommendations were introduced by the Expert Group on Biological Agents of the Interdepartmental Commission for Maximum Admissible Concentrations and Intensities for Agents Harmful to Health in the Working Environment [61, 62].

Quantitative analysis of biological aerosols

HBAs pose the most common risk when transported aerogenously as biological aerosols. For human health it is extremely important to know not only the composition of bioaerosols, but also the level of their concentration. The basic parameter for exposure assessment is the aerodynamic diameter of inhaled biological aerosol particles which determines their deposition in specific sections of the respiratory system, which translates into interaction between biological aerosol particles and human body cells [63]**.** Additionally, the mechanism of particle deposition is shaped by the air velocity, breathing technique, and lung ventilation volume, which, in turn, depends on a person's age and the dynamics of their activities. It is important to note that children and adolescents are particularly susceptible to poor air quality due to the incomplete development of their lungs and narrower airways. Furthermore, in relation to their body mass, children and adolescents inhale more air than adults [64].

The conditions for air sampling at workplaces in Poland regarding microorganisms (their total number and the number of microorganisms capable of growth) and bacterial endotoxins are specified in the standards PN-EN 13098:2020-01, PN-EN 14031:2021-12, and PN-EN 14583:2022-05 [65-67]. In order to obtain information about bioaerosol levels, a device for the active collection of airborne microorganisms should be used. Despite the continuous development of aspirational methods, many laboratories still use Koch's method as the primary method for assessing the concentration of biological aerosols. This method involves calculating the concentrations of bioaerosols based on deposition measurements. However, there is no strict physical relationship between concentration and particle deposition, making this method not only imprecise but inherently inappropriate.

Own research conducted in 2009-2010, aimed at comparing the concentrations of bacterial and fungal aerosols obtained using the Andersen impactor and open Petri dishes, allows to conclude that particle deposition was weakly correlated with particle concentration, both for total concentrations and for concentrations of two size fractions [68]. It should be emphasized that this does not mean that for certain specific spaces, these correlations cannot be significantly higher. In such cases, it is possible to calculate the values of bacterial or fungal aerosol concentration based on measured deposition levels, but only for a specific, particular space and only for certain micro-meteorological conditions for which the concentration-deposition relationship has been obtained. However, even a slight change in these parameters would make it impossible to accurately determine the value of bioaerosol concentration based on measured deposition, which effectively means only very limited applicability of the Koch method.

In 2010 in Portugal a comparison was made between active bioaerosol sampling methods and deposition methods [69]. It was shown that there were significantly lower correlations between concentration and deposition of bioaerosol particles in the outdoor environment compared to results obtained indoors, due to the multitude of factors influencing bioaerosol concentrations in the outdoor environment. Canha et al. [69] highlighted the simplicity and low cost of the deposition method, as well as its effective application only for qualitative analysis of bioaerosols.

Therefore, to obtain information regarding the concentration of biological aerosols, it is necessary to use a device for active sampling of microorganisms suspended in the air, while the collection of bioaerosol particles by deposition method is justified only when sufficient information about the level of bioaerosol deposition or knowledge about the species composition of microorganisms is available.

The issue of the accuracy of bioaerosol concentration measurements was first addressed in 1990-1991 at the University of Cincinnati in the USA [70,71]. Basic measurement criteria were developed at that time, linking various types of aspirators with types of microorganisms and sampling time with the expected bioaerosol concentration.

The fundamental method for measuring bioaerosols is based on air sampling (aspiration), followed by separation of aerosol particles using various forces such as inertia, electrical, or thermal forces. For this purpose, air is usually blown through a special filter material or the direction of airflow is abruptly changed. In the first case, particles are deposited on the filter due to the complex interaction of different forces between aerosol particles and the filter material. In the second case, the phenomenon of inertial impaction is utilised, as aerosol particles, under the influence of inertia, collide with a special collection plate, where they remain deposited. Aspirators in which particle collection occurs due to inertial impaction are called impactors. In these devices, aerosol particles with sufficiently high momentum exit the curving airflow and deposit onto a collector.

Methods of improving microbiological IAQ

Developing a comprehensive strategy to enhance microbiological IAQ within educational buildings necessitates the implementation of multifaceted approaches targeting the mitigation of microbiological contaminants. These approaches encompass ventilation strategies aimed at facilitating air exchange to expel microorganisms, alongside the deployment of advanced air purification systems equipped with filters capable of capturing suspended particulate matter and microorganisms.

In recent years, the use of various air purifying devices has become increasingly common in order to improve the microbiological quality of indoor air. The growing interest in air purifiers is evidenced by initiatives such as the educational campaign "Mogę! Zatrzymać Smog – Przedszkolaku złap oddech" (I Can! Stop Smog – Preschooler, take a breath) conducted by the Marshal's Office of the Silesian Voivodeship between 2019 and 2021. Through this campaign, over 500 portable air purifiers were distributed to preschools. It is important to remember that in order for an air purifying device to positively impact our health and well-being, it should be used in accordance with the provided instructions. Additionally, timely replacement of used filters is essential, as they can serve as an ideal source for the growth and proliferation of microorganisms. Moreover, the effectiveness of air purifiers is influenced by various factors, including their proper placement within the room, optimal selection of operating time, and the volume of the space being purified.

In 2020, long-term research was carried out on the effectiveness of air purifiers in one of the Silesian preschools, where during a 6-month research, a decreasing tendency in bacterial aerosol concentrations was found by an average of 18% as a result of the operation of portable purification devices [30]. Much better results were obtained in Korea in 2013-2014, where the effectiveness of removing bioaerosols by an air purifier was demonstrated in kindergarten rooms at 62% for bacteria and 55% for microfungi [72]. However, research conducted in a preschool in the Silesian Voivodeship showed that before starting air purifiers, the respirable fraction of bacterial aerosol (bioaerosol particles with an aerodynamic diameter $\leq$ 3.3 µm, capable of penetrating deep into the respiratory system) constituted on average 70% of the total bacterial concentration, and the operation of air purification devices reduced its share by an average of 20% [30].

Encouraging awareness among students, educators, and staff through educational endeavours underscores the critical importance of adhering to stringent cleanliness standards and implementing effective practices for maintaining optimal microbiological IAQ within educational settings.

Shaping indoor environment conditions through energy-efficient HVAC systems in educational buildings

Heating and cooling energy consumes a significant portion of a building's energy. In Poland, in the case of a newly built or retrofitted educational building, as well as other public utility buildings, the limit value of total Primary Energy for heating, ventilation, and domestic hot water preparation is 45 kWh/(m^2×year) [37]. To meet this requirement, traditional design solutions for HVAC systems cannot be applied anymore. Energy can be saved by preventing its escape (using effective insulation of building partitions), recovering it (e.g. through mechanical ventilation with heat recovery), and using energy-efficient heat sources. A modern heat source not only provides economic benefits but also contributes to environmental goals by reducing emissions from the combustion of conventional fuels.

The biggest challenge concerns the existing buildings which need to undergo deep renovation. Large-scale retrofitting of schools improves the energy parameters of buildings, but, as a rule, does not contribute to improving the air quality in classrooms. Significant improvements in the energy parameters of buildings require a substantial increase in the airtightness of their building envelope and other structural elements. Retrofitting is often limited to adding additional thermal insulation of external partitions and replacing windows and doors. After carrying these activities out building's heat loss is minimised, leading to cost savings on heating. However, such airtight building also has its drawbacks as it often lacks fresh air. Frequently, as a result of window replacement and sealing, the air quality in classrooms deteriorates. This issue is particularly acute in older educational buildings that rely on natural ventilation, i.e. opening windows. At the same time, it results in heat loss through windows that are unsealed for ventilation purposes. Increasing the airtightness of the building and limiting the ventilation air volume flow rate may not necessarily reduce the amount of energy needed for heating. This is due to increased energy consumption at the beginning and end of the heating season when building occupants protect themselves against overheating by opening windows while the radiators are on. Ineffective thermal management in the building prevents the full potential of retrofitting from being realised, leaving energy-consuming, low-quality, inefficient installations in the facility.

The vast majority of old educational buildings are equipped with a traditional natural (gravity) ventilation system, which operates depending on outdoor air conditions [73]. This system does not allow for control over the quantity and quality of exchanged air, thus failing to provide sufficient air exchange. Even if such exchange occurs, it does not facilitate the conditioning of dusty supply air or the recovery of energy (heat and cold) from the exhausted air. The lack of efficient ventilation leads to pollutant levels exceeding permissible values several times. It also hinders protection against microbiological threats and smog during the heating season. Consequently, in buildings without mechanical supply-exhaust ventilation occupants' comfort is reduced due to poor air quality [74, 75]. Increased building tightness reduces air exchange in rooms, resulting in elevated CO_2 levels, often reaching values that can lead to acidification of the body. Additionally, indoor air relative humidity increases, leading to the presence of mycotoxins in the air as a result of indoor mould contamination.

Therefore, an adequate supply of fresh and ventilation air should be ensured in educational buildings. According to the standard [76], in schools as public buildings intended for the permanent and temporary stay of people, the required volume flow rate of outdoor air should be a minimum of 20 m^3/(h·person) for adults. In preschools and nurseries, the required flow rate is 15 m^3/(h·person) for children. On the other hand, the standard [40] provides requirements for the volume flow rate of ventilation air, not outdoor air, depending on pollutant emissions, the presence of people, and air quality. These requirements are typically assigned to the aforementioned categories I-III. For example, the requirements for category I are as follows – the design unitary ventilation air volume flow rate for unadapted individuals is 10 l/(s·person). This value results from the presence of occupants. To dilute pollutant emissions, this flow rate should be 0.5 l/(s·m^2) for very low-emission buildings, also in category I. Importantly, for health reasons, the non-exceedable level of minimum air volume flow rate is 4 l/(s·person).

Further requirements can be found in a number of foreign literature sources (described in the compendium [35]) among which detailed information is available in the ASHRAE guidelines [49]. For specific educational rooms, these requirements are as follows:

- nursery rooms (for children up to 4 years old) – 18 m^3/(h·person), i.e. 5 l/(s· person) and 3.2 m^3/(h·m^2), i.e. 0.9 l/(s·m^2),
- classrooms (for children aged 5–8 years) – 18 m^3/(h·person), i.e. 5 l/

(s·person) and 3.2 $m^3/(h \cdot m^2)$, i.e. 0.9 l/(s·m^2),

- classrooms (for children aged 9 years and above) – 18 m^3/(h·person), i.e. 5 l/(s·person) and 2.2 $m^3/(h \cdot m^2)$, i.e. 0.6 l/(s·m^2),
- lecture rooms – 13.4 m^3/(h·person), i.e. 3.7 l/(s·person) and 1.1 $m^3/(h \cdot m^2)$, i.e. 0.3 l/(s·m^2) [35].

The optimal retrofitting of educational buildings must encompass actions aimed at improving the indoor environment quality of classrooms [10]. A proper approach involves changing the ventilation method of educational facilities from inefficient and uncontrolled natural ventilation to balanced, efficient mechanical system. Changes in climate and the need for energy conservation also dictate the installation of sustainable systems in schools. In educational buildings HVAC solutions should perform well during both summer and winter months, be quiet, energy-efficient, and equipped with reliable indoor air temperature control. Classrooms also pose a challenge in terms of cooling. Whenever possible, rooms should be ventilated, e.g. during breaks between classes. However, opening windows does not always provide sufficient cooling and ventilation during warm months. In such case, mechanical cooling is required during lessons. Retrofitting old school buildings often presents challenges in finding suitable technical solutions. The architecture used decades ago does not meet today's requirements. Therefore, specific solutions are often necessary. A significant problem in reducing energy consumption in educational buildings is that almost none of the existing schools have the capacity to introduce large-scale supply and exhaust ventilation ducts into their structures. Traditional chimney ducts used in gravity ventilation are particularly unsuitable for active ventilation.

A modern ventilation system for educational buildings should be based on air handling units (AHUs) equipped with heating (and cooling) coils powered by heat pumps with sufficient capacity for heating classrooms at design temperatures. This would enable the electrification of heating systems in schools with a significant share of renewable energy sources. The AHUs should be equipped with controllers regulating the indoor air parameters in the classrooms. By adjusting the ventilation air volume flow rate to the current demand for fresh air and achieving a high level of heat recovery, heating costs could be significantly decreased. Air filters, an appropriate air distribution system, and controlled ventilation air exchange rates based on CO_2 levels ensure not only a substantial increase in the efficiency of educational processes and protection against smog but also effective prevention of the spread of airborne diseases, including coronavirus pandemics. A key element should be a management and supervision system regulating the operation of AHUs controllers. This system should be flexible enough to allow the connection of additional classroom units. It should enable monitoring air parameters in individual classrooms and remote control and diagnostics of the ventilation systems installed in each room of the school.

Educational facilities are characterised by dynamic variability in thermal load. Each building has a different heating and cooling demand and the supply air volume flow rate. This results from the schedule of classes and the number of occupants participating in them. To meet these requirements, systems providing thermal comfort conditions to occupants should be flexible and have low inertia of operation. Such results can be achieved by using decentralised ventilation and air conditioning systems with indoor units in each room [77, 78].

Decentralised mechanical ventilation systems feature a recuperator (heat recovery unit) that allows for the recovery of heat and moisture, ensuring that the air supplied to the rooms is not dehumidified. The performance of these devices can be controlled based on the CO_2 level in the classroom. This means that the recuperator will adjust its efficiency depending on the number of occupants. Automation technology will control the indoor air temperature to optimise its operation. In summer, if the outdoor air temperature is lower than the exhaust air temperature, the device can automatically switch to cooling mode. If the technical conditions of the building permit, wall-mounted recuperators can be a suitable solution. These devices are installed inside the room, with the air intake and exhaust located on the external wall of the building. An example of a ventilation air heat recovery unit installed in a school complex in Końskie, Poland is presented in fig. 6.

The air conditioning systems designed for educational facilities can be classified as indirect and direct systems. Indirect systems involve devices that work to prepare pre-conditioned air, such as in AHUs. For educational buildings, cascade systems are recommended, offering a broad range of cooling and heating power regulation. The automation module adjusts the number of devices operating simultaneously based on the current power demand. Additionally, during the winter season when heating the air, outdoor units undergo a defrosting process involving the reversal of the refrigeration cycle to eliminate frost from the heat exchanger. Communication with the control system can be accomplished using analogue or digital signals. This allows for time savings in installation, as it does not require complex wiring.

The second type is a direct air conditioning system, which can include Split and Multi-Split units as well as Variable Refrigerant Flow (VRF) systems. Their task is to ensure thermal comfort in the shortest possible time. When choosing this system, special attention should be paid to the type of indoor units and, consequently, the air distribution method. For educational facilities, cassette-type indoor units are recommended due to the air supply method, which utilises the Coanda effect, i.e. the adherence of the air jet to the ceiling, as well as easy maintenance. This type of device can precisely control the indoor air temperature and adjust its power according to the number of occupants in the room. An example of a VRF cassette indoor unit in a preschool classroom is presented in fig. 6.

Additionally, a Variable Air Volume (VAV) or demand-controlled ventilation system can continuously collaborate with the AHU to ensure that only the necessary air volume flow rate is delivered to rooms [75]. Indoor environment conditions can be monitored by sensors inside the building through the measurement of air temperature and IAQ, e.g. CO_2 level. This allows for adjustments to the HVAC system only to the extent necessary, depending on whether the building is occupied or vacant.

Fig. 6.
Examples of ventilation and air conditioning systems' units in school buildings: VRF cassette indoor unit [79] (on the left) and heat recovery unit (recuperator) [80] (on the right)

Educational buildings are very dynamic in terms of heating [81]. Periodic use, empty rooms at night and on weekends, as well as high and rapidly changing thermal loads on weekdays, require a quick response from the heating system. Also, heating the classrooms before the return of students and staff must be done quickly and efficiently. Classrooms typically have large windows to make use of natural light. During the heating season, the surface of the windows is cooler than other surfaces in the room, causing asymmetry in thermal radiation, which students sitting near the windows may find uncomfortable.

In the case of educational buildings, the most commonly used solution is the installation of water central heating radiators. It ensures the maintenance of the thermal comfort conditions and guarantees a quick response to changing heat demand. Radiators placed below windows compensate for cold sensation and prevent the flow of cold air through the window. In some types of educational buildings or rooms, the best solution is to use underfloor heating. Capillary mats or infrared heating in the form of infrared radiators can also be applied as additional or primary heating in schools.

Renewable thermal and cooling energy sources in educational buildings include heat pumps, which can operate in both heating and cooling modes. Examples of different heat pump technologies include air-source heat pumps, ground-source heat pumps and VRF systems [81-83]. Ground-source systems are most commonly installed to meet the heating and cooling needs of an entire building or campus buildings. Gas absorption heat pumps or trigeneration units can also be used. When upgrading the heat source in an educational building, a hybrid approach can be applied. For instance, a school could install heat pumps to serve part of the building, thereby reducing dependence on existing gas boilers. Due to the use of air as the heat source in air-source heat pumps, the efficiency of the devices decreases with a decrease in outdoor air temperature. In situations of significant temperature drop (during the winter season when heat demand is the highest), heat pumps are supported by a gas boiler. This ensures efficient operation of the heating system and provides safety in the harshest conditions. Moreover, such a system guarantees very high efficiency and appropriately low investment costs. Additionally, the system can collaborate with a solar installation, which can pre-heat the heat carrier fluid and charge the central heating buffer tank and the domestic hot water tank. An example of a cascade of air-source heat pumps in the Primary School in Dęba, Poland, and a ground-source heat pump installation in Buckley Elementary in Connecticut, USA, is shown in fig. 7.

Fig. 7.
Cascade of air-source heat pumps in the Primary School in Dęba, Poland [84] (on the left) and installation of a ground-source heat pump – supply and return from the ground heat exchanger in Buckley Elementary in Connecticut, USA [85] (on the right)

The optimal solution in the context of heating electrification is to combine several units into a compact HVAC system, supported by recovered heat from the exhaust air, powered by an air or ground-source heat pump and supplemented with energy storage. Such a system should be equipped with controllers that oversee the operation of entire system, acting as the centres for the energy efficiency of the building, managing thermal comfort, IAQ, and energy consumption. When combined with photovoltaic installations connected to smart power grids or equipped with electrical energy storage, this represents the future of intelligent building construction including educational buildings. HVAC solutions will continue to evolve. The integration of innovative technologies such as artificial intelligence and machine learning has enormous potential for further optimising energy efficiency and managing the quality of educational environments. These technologies can intelligently analyse data, predict usage patterns, and proactively adjust HVAC settings to maintain a healthy and comfortable learning environment.

Summary

From the perspective of the number of hours spent in educational institutions, a comprehensive approach to optimal thermal and humidity conditions, thermal comfort and IAQ becomes a key aspect of caring for the well-being of pupils and students. Ensuring optimal indoor environment conditions in educational facilities significantly contributes to improving health, enhancing the comfort of learning and work, and boosting overall well-being. Implementing actions focused on monitoring and maintaining high IAQ, including microbiological IAQ, in educational institutions is key to creating an environment that supports the health of students and school staff. It is crucial that awareness of this issue encompasses both individuals in managerial positions and those responsible for occupational safety and hygiene.

The starting point for the presented paper was a literature review of selected studies regarding thermal comfort conditions and IAQ in educational buildings. They revealed numerous issues related to too high CO_2 levels and thermal discomfort, which were mainly the result of ineffective natural ventilation and the lack of necessary air volume flow rate, and the presence of respirable fractions in the air that can penetrate deeply into the respiratory system during inhalation, leading to serious health problems. At the same time, there is a lack of uniform legal regulations and recommendations concerning the thermal and humidity parameters and air quality in educational buildings, which are crucial for both their designers and occupants.

In the presented paper:

- the review of selected legal regulations and recommendations regarding air temperature, humidity, velocity and CO_2 level values in educational buildings was carried out. It was based on Polish and international standards, as well as guidelines from ASHRAE, ISHRAE, and ISIAQ associations. On its basis it was concluded that, depending on the literary source, the indoor air parameters in educational buildings should be within the following ranges: air temperature, depending on the winter/summer period, from 18°C to 25°C; air velocity below 0,2 m/s, relative humidity, depending on the winter/summer period, from 30% to 70%; CO_2 level below 1000-1500 ppm.
- it was found that there are no universally applicable permissible exposure limits for HBAs in educational buildings, only proposed limit values of concentrations of

microorganisms, which can be helpful in assessing the exposure to these factors. HBAs proposed limit value in public buildings for fungi is 5.0×10^3 CFU/m^3 and for bacteria (all) is 5.0×10^3 CFU/m^3. It should be noted that for the respirable fraction the values should be half smaller [61].

- the methods for determining thermal comfort using the PMV-PPD model and adaptive model were described, along with presenting an example of measurement equipment for assessing thermal comfort conditions (microclimate meter), air velocity (multi-directional anemometer), ventilation air volume flow rate (balometer), and CO_2 level (CO_2 meter).
- possible retrofitting solutions of HVAC systems aiming to improve indoor environmental quality and increasing the educational buildings' energy efficiency were discussed. The commonly occurring natural ventilation system in classrooms should be replaced by a modern mechanical ventilation system with heat recovery, such as a decentralised ventilation system. Such an installation should be fully automated and adjust the ventilation airflow to current needs to reduce the level of CO_2. The HVAC installation should incorporate renewable energy sources such as air and ground-source heat pumps, photovoltaic systems, and enable both thermal and electric energy storage. By investing in advanced energy-efficient HVAC systems, schools and universities not only increase the productivity and well-being of pupils and students but also create a sustainable infrastructure in line with environmental goals.

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