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Review

Recent Achievements in Research on Thermal Comfort and Ventilation in the Aspect of Providing People with Appropriate Conditions in Different Types of Buildings—Semi-Systematic Review

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Abstract: Ventilation systems are mainly responsible for maintaining the quality of indoor air. Together with thermal comfort maintenance systems, they create appropriate conditions for living, working, learning, sleeping, etc., depending on the type of building. This explains the high popularity of research in this area. This paper presents a review of articles published in the years 2020–2023, which are indexed in the Scopus database and found with keywords "ventilation" and "thermal comfort" in conjunction with the type of building or predominant activity. Finally, 88 selected works for five types of buildings were discussed, namely offices, schools, hospitals, bedrooms, and atriums. Data on publications are summarized in the tables, taking into account the publishing year, country of origin of the authors, and keywords. In this way, the latest directions in research were presented, and research groups dealing with this subject were highlighted. For each type of building, synthetic conclusions were presented, summarizing the results of the analyzed research. This review paper would be helpful for scientists and practitioners in the field of ventilation in order to organize knowledge and in a short time be up to date with the latest research showing how ventilation affects the quality of use of buildings by their users.

Keywords: ventilation; thermal comfort; office; school; hospital; residential; atrium; sleep quality

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1. Introduction

Research on indoor air quality, thermal comfort, and ventilation is closely related to the IEQ (indoor environment quality) issue. People in developed countries with cold and temperate climates spend 90% of their lives indoors. Only 10% of their activity is outdoor activity. Therefore, it is extremely important to provide comfortable interior conditions in buildings. All research carried out around the world that concerns issues related to indoor air parameters brings valuable results that can be used in the various activities of engineers worldwide. Conclusions from experimental studies, field studies, surveys, or simulations indicate new directions for the actions of designers: architects, constructors, and installers. Taking into account the results of scientific research in one's professional activity should improve people's quality of life. This is the implementation of the sustainable development goals, in particular, Goal 3: good health and quality of life. The type of ventilation affects air temperature, humidity, and velocity in the room. However, ventilation rates impact carbon dioxide concentration and consequently air quality. The right ventilation strategy for the building allows thermal comfort and avoid a sick building syndrome (SBS). Due to the numerous scientific publications on the subject of thermal comfort and ventilation, it was considered necessary to review the results of the latest research in this area to set directions for further research and collect the most common results in a form that allows them to be used in engineering activities. Results of scientific research that are not disseminated and used in practice lose their importance. It is important, especially at a time when so many scientific articles are published around the world every day, to compile a list of the latest scientific achievements so that a direction for further research can be presented. It is also important to communicate research results to the public in the form of specific guidelines that can be taken into account in practice. An overview of the latest research and improvements in the field of ventilation systems published in 2020–2022 is presented in the review paper [1]. The article focuses on five key aspects related to ventilation systems: airtightness of buildings, demand-controlled ventilation, decentralized systems, earth-to-air heat exchangers, and heat recovery from removed air. Although the article showed a significant impact of the ventilation system on the energy consumption of the building, this topic was discussed in isolation from the issues of indoor air quality and thermal comfort. Our current article aims to fill this research gap. Nevertheless, in the introduction, which is the background of the current review, it is impossible not to pay attention to the issues related to energy demand, which is the cost of maintaining high air quality and/or thermal comfort. Various technologies for heat recovery [2], or methods of intensifying heat exchange in system components [3–5], as well as the use of decentralized ventilation systems [6–9] or earth-to-air heat exchangers [10,11], positively affect the reduction in energy consumption in the energy audit of the building [12]. The energy-saving effect can also be obtained by using heat recovery from domestic hot water [13–16], but it is easier to achieve it in mechanical ventilation systems [17]. It should be emphasized that thermal comfort is also affected by factors other than ventilation, such as the radiation temperature of the surrounding surfaces, which is easily obtained using surface heating [16,18,19], radiators [20] or wall panels with heat pipes [21] and others [22,23], as well as outdoor sources [24,25].

The purpose of this review paper, which concerns issues related to the parameters of the indoor environment, assessed through the prism of thermal comfort and air quality as a function of ventilation for selected types of buildings, is to indicate the direction of scientific research for specific topics, together with the possibility of using the results in engineering practice.

2. Materials and Methods

A semi-systematic review based on the methodology provided by Synder [26] was conducted. This type of review is appropriate for overviewing research and tracking development over a chosen period of time. Our desired contribution to the field is to show the main themes found in the literature related to the specified scientific problem in a broad way. We intended to analyze the content of the articles, show how scientists research a particular topic, and present the traditions of those studies in a given area. We see the need for such a review on the topic of thermal comfort and ventilation in selected buildings because the number of articles published each year is increasing, which makes it difficult to review the latest news in the field even for a short period of time. We decided to review research conducted recently for a community that is familiar with the topic and is interested to find out what is new in the subject without having to spend many hours browsing through dozens of works. Our contribution is an analysis of recent works in order to summarize the most important conclusions and identify areas of current interest for researchers and possible directions for further research (what challenges are indicated by the results of recent works). Such an analysis requires dozens of hours of work and must be carried out by a person with knowledge in a given field. For this reason, our team has chosen the topics in which we conduct research and teaching.

We selected two research questions to which answers were sought:

Research Question 1: What research is conducted on thermal comfort and ventilation in terms of people's functioning in different types of buildings?

Research Question 2: What research methods have been used in recent years?

A literature review based on the proposed methodology was performed. The answer to the first question is a narrative description of the research in the selected articles, presented in Sections 3–7. The answer to question 2 is presented in Section 9 in the form of summary tables and analysis of the data collected in the review.

This review of scientific and conference articles was based on the assumption that the articles should be related to a specific topic and to be published in the years 2020–2023 (May). Publications were selected by choosing specific keywords: thermal comfort and ventilation. In order for an article to be included in the review, the selected keywords had to appear in the title, keyword set, or abstract of the article.

Various types of building uses were also selected and a review was conducted to assess ventilation and thermal comfort studies for offices, schools, bedrooms, hospitals, and atrium buildings. The analysis of the published results was carried out by narrowing down the review to the assessment of air parameters in the room by limiting it to the form of additional keywords related to the activity of people in these selected types of rooms. For offices, additional words: "work" and "productivity" were introduced, thanks to which the articles reviewed were narrowed down to those in which the impact of indoor air quality or thermal comfort parameters on work productivity was analyzed. In the case of schools, the scope was limited to the word "learning" to assess the impact of air parameters on learning and knowledge acquisition. In residential buildings, the influence of air parameters on "sleep quality" was taken into account. Due to the specificity of the operation of hospitals and other rooms, the search was not limited to specific activities of people in these rooms due to the fact that publications on these rooms are not very numerous, and the type of room itself defines the way it is used. Papers that met all the selection criteria but did not strictly concern people's satisfaction or the impact of air parameters on their functioning were rejected by the authors and marked accordingly in the text.

The following methodology was used for this review:

1. Specification of the subject of interest, which is "thermal comfort and ventilation in the aspect of providing people with appropriate conditions in different types of buildings"
2. Selection of the database to analyze. The review is limited to the SCOPUS database.
3. Selection for the types of buildings or rooms to be covered by this review and the time range for the articles. The "office", "school", "hospital", "bedroom", and "atrium" buildings are selected, and the database is limited to those articles, where at least one of the listed building types appears in the title, keyword set, or abstract of every analyzed article. The review is limited to articles published in the years 2020–2023 (May).
4. Selection for the main criteria that articles should meet to fit into the area of interest, which are set as the appearance of the following specific keywords in their titles, keyword sets, or abstracts: "thermal comfort", and "ventilation".
5. Screening of the filtered database and including additional keywords related to the typical expected indoor activity for selected types of rooms:
    a. "Work" and "productivity" for "office" buildings;
    b. "Learning" for "school" buildings;
    c. "Sleep quality".
6. For each type of building selected for this review:
    a. All review articles fitting the selected search criteria are included for review and discussion.
    b. For research and case-study articles, the screening is carried out for eligibility with the topic of interest, and all articles considered to be relevant to the subject of the review are included for review and discussion.

Figure 1 shows the adopted working methodology. Following this methodology, 53 scientific and conference papers were reviewed.

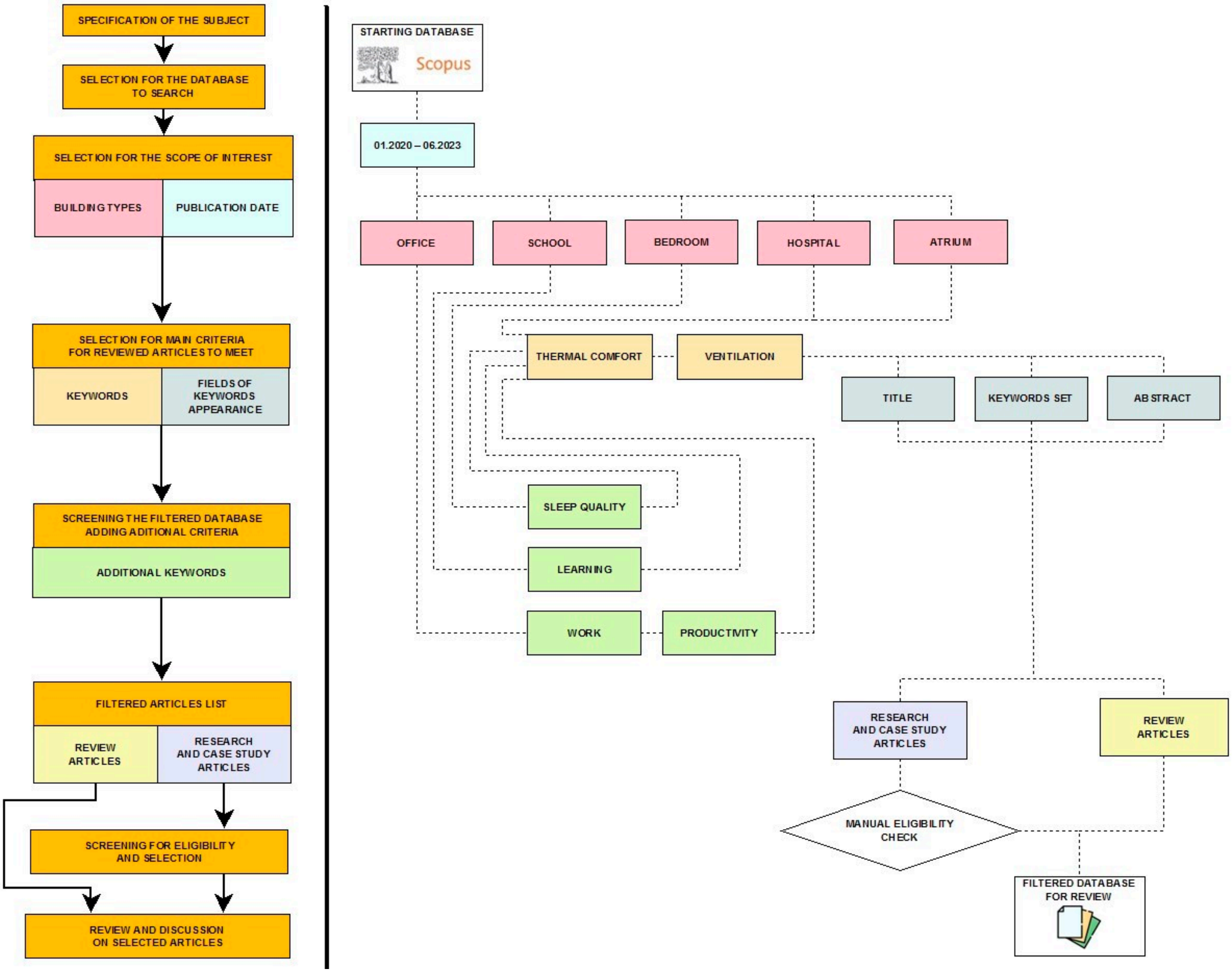

Figure 1. Review methodology.

The article partly concerns the period during which the COVID-19 pandemic lasted. Despite this, the review did not include works that would highlight the importance of the pandemic for this topic. During the COVID-19 pandemic, most public buildings operated in an unusual way—the number of users was limited, time intervals were applied between shifts, remote work was preferred, etc. Knowing that the virus can be transmitted by droplets, ventilation was intensified by increasing the streams of air supplied through the control system (mechanical ventilation) or more often windows were opened/rooms were ventilated (natural ventilation). In this unusual situation, the goal was to avoid the risk of infection without the feeling of thermal comfort or concern for the energy efficiency of the ventilation system. This is reflected in the research conducted in the field of ventilation during the COVID-19 pandemic, which mainly referred to the risk of virus transmission via the ventilation system. The issues of thermal comfort and the impact of the ventilation system on the quality of activity performed in a given room were not taken into account. It is therefore not surprising that none of the articles selected for review in this article were related to the COVID-19 pandemic. The subject of the review carried out as part of this work is thermal comfort and ventilation in the aspect of providing people with appropriate conditions in offices, schools, hospitals, bedrooms, and atriums during the typical use of the building—not in the exceptional situation which was the COVID-19 pandemic.

3. Thermal Comfort and Ventilation in Office Buildings vs. Productivity

Many people doing office work spend most of their time in buildings (usually at least 40 h a week) [27]. Worker well-being and productivity depends on conditions in the workplace. Therefore, it is important to provide indoor environmental quality (IEQ). One of the crucial parameters is the thermal comfort that is maintained by heating, ventilation, and air conditioning (HVAC) systems.

Between 2020 and 2023, according to the Scopus database, with the search criteria selected for this review (title, abstract, or keywords including "thermal" and "comfort" and "ventilation" and "productivity"), no review papers were published; however, eight original studies were found and reviewed in this section.

In the paper [28], Peng B. and S.J. Hsieh noted that thermal comfort measurements are often simplified and do not provide adequate control, and traditional control models are unable to adjust indoor environmental conditions to individual requirements. They proposed a data-driven thermal comfort model and HVAC control system which took into account occupant variability and could improve the thermal comfort of occupants in an open-space office room by 43.4–69.9% with slightly lower energy consumption (1–3.6%). The analysis was conducted for buildings equipped with HVAC systems. The support vector machine (SVM) algorithm (Gaussian kernel function, kernel scale—6.68, box constraint—Inf, epsilon—0.008, standardized, 20% of outlier fraction) and the artificial neural network (ANN) algorithm (parameters—Levenberg–Marquardt algorithm, 10 hidden layers, 20% in the validation set) achieved convergence of R^2 = 0.99 with 50 training data points; however, ANN required a shorter training time and had slightly better prediction test performance with 200 training data points (R^2 = 0.9962) and mean squared error (MSE = 0.0289). The limitation of data-driven models was the necessity for training, and they performed worse in cold-start scenarios than the PMV model (especially for the first day). For cold start scenarios, high accuracy and rapid computing time, a multistage hybrid model (PMV-SVM-ANN) was developed. The PMV-SVM-ANN model proved to be a statistically significant improvement over the SVM model. Control algorithms and data-driven thermal comfort can be used in commercial office buildings equipped with building management systems and smart thermostats.

In article [29], a transfer-learning-based multilayer perceptron model was presented. It was developed in order to make thermal comfort prediction more precise. The authors used the ASHRAE RP-884, Scales Project and Medium US Office datasets. They took into account only buildings with HVAC systems in 'temperate' climate zones. They developed a transfer-learning-based multilayer perceptron (TL-MLP) model and transfer-learning-based multilayer perceptron model considering climate zone (TL-MLP-C*). They predicted occupants' thermal comfort with insufficient labeled data.

The TL-MLP-C* model has better accuracy of thermal comfort prediction than popular knowledge-driven and data-driven models, (accuracy 54.5%). Combination of age, gender, outdoor environmental features, and the factors from the PMV model gave the best prediction of thermal comfort.

In article [30], measurements of thermal comfort and indoor air quality in an open office within a green-certified building with mechanical ventilation system in the tropics were presented. Levels of thermal comfort, CO_2 concentration, and supply air rates were analyzed, and questionnaires about the indoor environment were conducted among employees. Physical parameters were in acceptable ranges, and 81% of the occupants founded that thermal comfort with high adaptation rates was provided. The neutral temperature was 23.9 °C, which is 1.3 K lower than predicted (25.2 °C). The obtained results can be used to improve thermal comfort by adjusting the air temperature setting according to the real requirements of occupants in offices of a tropical green campus building.

Badeche and Bouchahm [31] studied the impact of large glazing areas on thermal comfort as well as visual comfort. They analyzed office building with natural ventilation and a deep room configuration in Algeria (semi-arid climate). The measurements were conducted according a post occupancy evaluation (POE) method which include IEQ physical measurement, focus group meetings, structured interviews, visual records, occupant survey questionnaires, walkthroughs, and technical measurement of building structure, services and systems. Obtained results indicated that natural ventilation was unable to effectively control air flow and night ventilation absence reduced the release of accumulated heat gains. Extensive solar gains caused overheating. In northeast- and southeast (NE-SE)-oriented rooms, temperature was higher than the temperature of thermal comfort during 96% of working time, during 86% of working time in the northeast (NE)-oriented rooms, and 100% in southeast- (SE) and southwest (SW)-oriented rooms. The mean internal temperature was 29.78 °C, and the maximum temperature was noticed in the southwest orientation and was equal to 38 °C. At the same time, daylight was not sufficient: areas near to glazing were overlit and areas in the rear were ill-lit. The authors suggest using an adaptive solar façade, smart glazing, and moving shading devices.

In article [32], parametric airflow evaluation of skylights, was conducted using software ANSYS Fluent 2019. The research in the admissions office with natural ventilation, located on the ground floor in the eight story educational building in Ecuador, was carried out. Thermal comfort was assessed by use of the predicted mean vote (PMV) and the predicted percentage of dissatisfied (PPD). Eight scenarios that took into account the opening area of skylight, distributing louvers along the skylight, door position (open or close), and impact of furniture on air movement in the room were analyzed. The best internal airflow performance was obtained by use of the 8 louvers 18 inches high by 60 inches wide: individual effective area was equal 0.23 m^2 and a total area was 1.84 m^2. In addition, the solution is more homogeneous, avoids turbulence, and can be more controlled. The results indicated that opening the door increases ventilation rates by 30%. Indoor air temperature equaled 18 °C and air speed in range: 0.25–0.75 m/s represented cool sensation (clothing level = 0.65) and slightly cool sensation (clothing level = 1.0). On the other hand, when the temperature was equal to 25 °C, thermal comfort was met.

Adjusting the opening distance of a tipping window by use of the predicted mean vote (PMV) in paper [33] was studied. Tipping shutter distance equaling 10 cm, 30 cm, and 60 cm was taken into consideration. The office was located on the seventh floor of a university building located directly on a busy street. The obtained PMV value was in the range 2.23–3.27 (warm-hot thermal sensation) and was correlated with wind velocity. In order to achieve a natural range of sensation, the authors recommended to apply a hybrid air conditioning system or mechanical aids.

Borsos, Á. et al. [34] developed a “comfort map” that takes into account individual preferences of indoor environment quality (IEQ). They used a comfort survey to assess thermal comfort, air quality, visual comfort and acoustic comfort as well as health risk factors and negative comfort sensation of each IEQ parameter. The research was conducted in an office building in Hungary and included 216 occupants; 65%, 50%, and 47% of respondents were dissatisfied with the adjustability of noises and sounds, ventilation, and thermal conditions in the work environment, respectively. The authors investigated the relationship between IEQ parameters and the employees’ comfort sensation. The developed comfort map shows IEQ parameters: thermal comfort (PMV, PPD), air quality (CO_2 concentration [ppm]), acoustic comfort (RT60 [s], LA [dB]), and visual comfort (daylight factor [%]) for each workstation.

Paper [35] presents the analysis of the working from home experience on the COVID-19 pandemic. As it is a specific case not related to typical office buildings, this paper is not reviewed.

Table 1 presents the list of publications on ventilation, thermal comfort, and productivity in office buildings.

Table 1. List of publications on ventilation, thermal comfort, and productivity in office buildings.

Authors	Year	Title	Journal DOI	Keywords
[28] Peng B., Hsieh S.-J.	2023	Cyber-Enabled Optimization of HVAC System Control in Open Space of Office Building	Sensors 10.3390/s23104857	cyber-physical system; HVAC; thermal comfort model; artificial neural network; support vector machine
[29] Gao N et al.	2022	Transfer learning for thermal comfort prediction in multiple cities	Building and Environment 10.1016/j.buildenv.2021.107725	human–building interaction, thermal comfort, transfer learning, HVAC automation, smart building
[30] Yong, N.H. et al.	2022	Post-occupancy evaluation of thermal comfort and indoor air quality of office spaces in a tropical green campus building	Journal of Facilities Management 10.1108/JFM-12-2020-0092	green campus building; indoor air quality (IAQ); neutral temperature; open-plan office; post occupancy evaluation (POE); thermal comfort
[31] M. Badeche, Bouchahm Y.	2021	A study of Indoor Environment of Large Glazed Office Building in Semi-Arid Climate	Journal of Sustainable Architecture and Civil Engineering 10.5755/j01.sace.29.2.28008	fenestration, indoor environment, post occupancy evaluation, thermal comfort, visual comfort
[32] Ortiz, M.C., Morales, S., Cabrera, V.	2021	Bioclimatic Optimization: Skylight Ground Floor New Building, Udla Park Torre II	Proceedings of International Structural Engineering and Construction 10.14455/ISEC.2021.8(1).AAE-18	bioclimatic design, natural ventilation, effective area, tropical climate, energy efficiency, thermal comfort, building performance, educational building
[33] Lahji K., Puspitasari P.	2023	Thermal comfort analysis by adjusting the tipping window opening distance using PMV	AIP Conference Proceedings 10.1063/5.0120286	not provided
[34] Borsos, Á. et al.	2021	The Comfort Map—A Possible Tool for Increasing Personal Comfort in Office Workplaces	Buildings 10.3390/buildings11060233	exploratory research; indoor environment quality; multidisciplinary approach; workplace health and well-being
[35] McGee B.L. et al.	2023	Work from Home: Lessons Learned and Implications for Post-pandemic Workspaces	Interiority 10.7454/in.v6i1.259	COVID-19, biophilic design, work from home, office design, post-pandemic design

In the analyzed articles, productivity was taken into consideration only as an issue correlated with IEQ parameters. There was no definition and comparison of work productivity in the context of better or faster work. In order to assess thermal comfort questionnaire surveys, experimental measurements and simulations using PMV (Fanger), adaptive and data-driven thermal comfort models were employed. A review of recent articles on ventilation and thermal comfort in the context of work productivity showed two main trends:

- Optimization of HVAC system by use of the machine learning algorithms to predict and control a thermal comfort considering occupants' individual IEQ preferences and climate;
- IEQ parameter assessments in office buildings with natural ventilation indicate that maintaining thermal comfort is difficult. Large glazing areas in office buildings are one of the main reasons. They cause overheating.

4. Thermal Comfort and Ventilation and Its Effects on Learning at Schools

Students spend 6–8 h a day at school [36], over many years. Effective learning requires a friendly environment. Air quality, thermal comfort, but also furniture ergonomics or interior aesthetics will affect the ability to learn and the well-being and health of children and young people learning. In order for children and young people to have a chance for the best possible development and exploration of knowledge, it is our duty to recognize the impact of the environment and minimize its negative impact on pupils and students.

Between 2020 and 2023, according to the Scopus database, with the search criteria selected for this review (title, abstract, or keywords including "thermal" and "comfort" and "ventilation" and "learning" and "school"), 18 original studies were founded and reviewed in this section.

The way in which the space for children while they are learning is organized was the subject of a literature review carried out in [36,37]. Based on an analysis of 68 articles, the authors [36] concluded that a pleasant, warm, and flexible learning environment is a key impact on students' well-being and performance. When designing schools, it is necessary to ensure the presence of charming colors and images, ergonomic furniture, and adequate acoustic and thermal comfort, ventilation and natural lighting. In [37], it was pointed out that contact with nature positively affects creativity and the ability to solve problems. Therefore, in classrooms and other places where students spend any amount of time learning, opening windows should be used to provide natural ventilation, which has been shown to improve both comfort and cognitive function.

Visual and thermal comfort was the subject of research conducted at a primary school in Semarang, Indonesia [38]. The authors showed that in tropical climates, especially in naturally ventilated buildings, relative humidity and temperature (dry air temperature) have an impact on the effective temperature in the room. To increase thermal comfort, the air speed in the rooms should be increased by using fans or providing cross-ventilation by placing openings in the façade that allow wind to penetrate into the building. Another method is to block direct sunlight entering the room to minimize the heat generated by solar radiation. However, it should be remembered that natural lighting should be in the range of 250–750 lux. Natural lighting strategies must be able to limit and control the level of solar radiation, especially from side and overhead lighting, to overcome the problem of heat distribution by providing shading and adjusting the size and placement of windows to produce indirect sunlight.

In Medan, Indonesia [39], primary school students spend 90% of their time in the same class. In situ tests were performed in one of the classrooms in the school building with natural cross-ventilation. It was shown that although there was overheating in the class (air temperature inside was 30.5–34.5 °C), the relative humidity in the class ranged from 57.2% to 74.6%, and the median CO_2 concentration ranged between 602 ppm and 637 ppm, while the median CO_2 concentration in the outdoor air was between 498 ppm and 520 ppm. The authors draw attention to the need for further research to assess the relationship between temperature and relative humidity and CO_2 levels in classes with natural cross-ventilation.

Research conducted in Poland [40] focused on the possibility of using a hybrid mechanical ventilation system and night ventilation in a school located in a passive building in the summer. In order to build a simulation model (simulations in Design Builder), the authors determined the value of students' metabolism, taking into account a smaller body surface area than adults, and at 108 W/person, the CLO value was 0.5. The comfort temperature range of 24 to 27 °C was determined. Simulation and empirical studies have shown that intensive night mechanical ventilation combined with high thermal insulation without the use of a ground heat exchanger or heat pump allows for a significant reduction in thermal discomfort in the building. However, it is not possible to completely protect the building during the hottest period of the year. It was also shown that students and teachers easily adapted clothing to the prevailing conditions. The article also proposes a method for determining the hour of discomfort. This method assigns a kc factor in the range of 0–4 depending on the degree of exceeding the comfort range. The products of the weighting factor and the number of hours for all intervals are summed up.

The authors of [41] performed simulation studies (Design Builder) and in situ measurements that were conducted in Nepal and also addressed the issue of a comfortable temperature for students. Based on the conducted research, they showed that the average comfort temperature was 26.9 °C, and the temperatures were in the range of 25–29 °C. In the results of surveys on students' perception of the indoor thermal environment, students preferred lower temperatures. No significant differences in feelings were noted according to gender.

Also, in Australia [42], a study was conducted among high school students in which it was determined that the comfortable temperature was in the range of 20.4–27 °C, with a neutral temperature of 23.7 °C in summer and 22.6 °C in winter. An equally important issue was air quality. In the subtropical climate of Australia, split air conditioners are often used to lower the temperature in classrooms. Studies have shown that in classrooms without a DCV (demand-controlled ventilation) system, CO_2 concentrations reached up to 2981 ppm in summer and 2418 ppm in winter, and in rooms with DCV ventilation systems, the peak concentration was 1335 ppm. In addition, volatile organic compound (VOCs) analyses were performed from air samples, and an improvement in air quality in the DCV class was demonstrated. The authors highlight the effect of both indoor temperature and CO_2 concentration on students' fatigue. Students demonstrated their ability to adapt to changes in room temperature. The time it takes for students to adapt to a rapid change in average outside air temperature is one week.

Measurement and survey research conducted in Selangor, Malaysia [43] focused on differences in thermal comfort in schools located in urban and rural areas. The optimal temperature range in the room is from 27.1 °C to 29.3 °C and it was exceeded in all analyzed facilities. Measurements showed that in urban areas the temperature increase was rapid, and in rural areas it was constant. The survey results confirmed that students and teachers lost concentration when the room was too warm.

The authors of [44] conducted a review of the literature on indoor environmental quality, air quality, and thermal, acoustic, and visual comfort in Indian schools. India is the seventh most densely populated country in the world, and its area exceeds 3 million km^2. They are divided into five climatic zones. The subject of the analysis was 37 articles. The authors concluded that the available research for India is convoluted and disorganized. They suggest the need to develop a well-established method for assessing classroom environments. This survey review uses the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) approach as the review methodology.

The prediction of thermal comfort based on machine learning was addressed by the authors [45]. The article draws attention to the fact that most of the machine learning solutions proposed for air-conditioned or ventilated buildings are intended for adults. A month-long study was conducted in five naturally ventilated school buildings in the city of Dehradun, India. The study included 512 primary school students. It was shown that the students were able to more accurately assess their thermal sensations than to show thermal preferences or thermal comfort levels. The ability to generalize thermal comfort models used in machine learning is highly desirable and achievable in neighboring school buildings with natural ventilation. Techniques such as SVMs (support vector machines algorithm) offer high predictive stability but need to be refined in practical applications. There are also new paradigms, such as transfer learning and multitasking learning. For high accuracy, TC models must be trained using spatial or building-specific data. Still, performance can vary in naturally ventilated buildings.

In China [46], numerical studies of CFDs (computational fluid dynamics) were carried out using the RANS model. They were aimed at assessing the structure of the school building in which classrooms are in the middle of the building, and on their sides, there are corridors, and the building is also equipped with ground heat exchangers. The building is located in Northern Shaanxi, where the average outside air temperature from October to

March is below 10 °C. It has been shown that the double-sided construction of the corridor is an energy-saving solution, because, thanks to them, you can achieve the effect of heat preservation and increase the temperature at the entrance. Ground ventilation pipes can increase the room temperature when the room is located downstairs, which can effectively improve the comfort of the room. A significant influence on the temperature in the room has the proportion of width to height of the window. As the ratio of width to the height of the window increases, the area of the window for ventilation will increase, which will accelerate the improvement of indoor air quality. However, if the window area is too large, the effect of thermal insulation of the room will be weakened.

Next, studies based on numerical simulations are described in [47]. It was planned to install an air conditioning (A/C) system in all primary schools in Yuan (Taiwan) within two years. Therefore, the authors performed simulation studies of various air conditioning control strategies for an average 8 h CO_2 concentration in the classroom. The optimal strategy of use is the operation of air conditioning throughout the school day in cooperation with a mechanical ventilation system ensuring the exchange of fresh air at the level of 5 L/s for each person in the room. If air conditioning is not installed and the classroom is cooled and ventilated only by natural ventilation, the average CO_2 concentration in the classroom varies between 583 and 612 ppm, depending on the percentage of students staying in the classroom during the break.

The article [48] presents the results of air quality tests that took place in two classes of a secondary school undergoing thermo-modernization renovation. The school is located in Bucharest, Romania. There were 25 students and one teacher in the study class. During the period of stay in the classrooms, the CO_2 concentration exceeded the maximum allowed value of 1000 ppm for almost the entire period, peaking at 3600 ppm. While maximum concentrations of O_3 during the study period exceeded 200 $\mu g/m^3$. The variability in ozone concentrations in classrooms is caused by ozone emissions from laser printers, but direct solar radiation also plays an important role in the formation of these concentrations. Children are more likely to develop asthma and other respiratory diseases as a result of prolonged exposure to high ozone concentrations. The main conclusion presented by the authors is the need to use ventilation in learning spaces.

The authors [49] performed a dynamic thermal simulation on three levels (housing, classroom, school building) to assess the resources of school buildings and explore the possibilities for improvement. The study was carried out for three locations representative of climate distribution in Europe: Southampton (United Kingdom) as a temperate oceanic climate; Brescia (Italy) as a warm temperate climate; and Thessaloniki (Greece) as a warm Mediterranean climate. Possible renovation strategies have been developed, taking into account both the heat transfer coefficient and thus the heat demand, thermal mass, and the dynamic heat transfer coefficient, i.e., the efficiency of the cooling season. The most effective retrofitting strategies to improve indoor comfort are natural ventilation; good shading; high thermal mass; good insulation; and night ventilation in summer. It was stated that passive strategies must be evaluated in an iterative process to choose the best option, given that the building must be comfortable all year round. In this regard, there is no unique strategy; however, it is important to emphasize that in temperate climates, the most effective involves the control of thermal inertia, taking into account both winter and summer performance. Thermal comfort in educational buildings in summer is possible to achieve in some regions with a temperate climate without the use of mechanical systems. In order to achieve thermal comfort conditions in rooms, it is also important to inform users about monitoring and building management.

The authors of [50] have developed a method to simulate school buildings located in the United Kingdom based on an adaptation of the modeling method originally used for energy modeling. A method was developed for the Data dRiven Engine for Archetype Models of Schools (DREAMS), an EnergyPlus-based inventory modeling structure that models different class typologies and takes into account not only indoor environmental quality criteria but also achievements, health, and healthcare costs. The results of the dynamic IEQ simulations showed that the impact of the construction age on learning performance rates existed and that it could be stronger in warmer regions.

In Milan, field studies were carried out in the Politecnico di Milano building in 16 air-conditioned and naturally ventilated rooms [51]. Thermal preference studies were also conducted among 985 students to assess the predictions given by the Ranger and adaptive comfort models. The authors confirmed the suitability of the Ranger model for predicting thermal sensations in air-conditioned classrooms with reasonable accuracy. In naturally ventilated classrooms, the adaptive model proved to be suitable for predicting students' comfort zones according to ASHRAE 55, while the adaptive comfort temperatures recommended by EN 15,251 were unacceptable for large numbers of students. There were no significant differences in the perception of thermal comfort between the sexes, except for two classes with natural ventilation, in which women's voices were closer to neutrality compared to men, who expressed warmer thermal sensations. Comparing the students' thermal sensation ratings with their thermal satisfaction showed that not all voices outside the comfort range always mean dissatisfaction, and vice versa.

A study of 583 primary school students in Galicia, Spain [52] confirmed the existence of a link between learning space and students' mathematical and artistic performance. It was also confirmed that the adaptation of iPEP scale (Indoor Physical Environment Perception scale) to measure students' perception of variables of the physical learning space in primary school is accurate and reliable. It was determined that the factorial structure of the learning-space construct consists of three factors: workplace comfort, natural environment, and building environment. The prognostic analysis of the results in mathematics confirmed a direct relationship with ventilation, room size, views, and attachment to the place.

A comprehensive review of research over the last 50 years on indoor air quality in classrooms in schools from over 40 countries is presented in [53]. The general conclusion that has been drawn from the analysis of the available literature is that students feel comfortable in rooms with a cooler climate than environments in which adults feel thermally neutral. Poor classroom air quality will result in the cognitive deterioration of students, with negative consequences for progressive learning while increasing short-term sick leave. Exposure to various air pollutants in school buildings threatens serious damage to the health of students, as they inhale a larger volume of air corresponding to their body weight than adults. In a number of studies the authors reviewed, [53] showed higher concentrations of pollutants in schools than in residential and commercial buildings. Volatile organic compound (VOC) pollutants are among the main indoor air pollutants, causing serious health problems for children and adults. In many schools, they have identified particulate matter pollution as the main source of indoor air pollution. In addition, Penicillium, Cladosporium, Aspergillus, and Alternaria were the most common fungi in school premises, and their prevalence varies according to climate and location, whether in the countryside or in the city. The authors note that there is a lack of research on the correlation between classroom CO_2 concentration and learning ability. Their analysis suggests that keeping classroom CO_2 levels below 900 ppm (absolute level) reduces the negative impact on learning.

Table 2 presents a list of publications on thermal comfort, ventilation and learning in schools.

Table 2. List of publications on thermal comfort, ventilation, and learning in school.

Authors	Year	Title	Journal DOI	Keywords
[36] Manca S.; Cerina V.; Tobia V.; Sacchi S.; Fornara F.	2020	The effect of school design on users' responses: A systematic review (2008–2017)	Sustainability 10.3390/SU12083453	learning space; psychological responses; school architectural features; students' performance; users' well-being

Table 2. *Cont.*

Authors	Year	Title	Journal DOI	Keywords
[40] Dudzińska A.; Kisilewicz T.	2021	Alternative ways of cooling a passive school building in order to maintain thermal comfort in summer	Energies 10.3390/en14010070	design builder; discomfort; energy efficiency; overheating; thermal comfort; weighted measure of discomfort
[41] Shrestha M.; Rijal H.B.	2023	Investigation on Summer Thermal Comfort and Passive Thermal Improvements in Naturally Ventilated Nepalese School Buildings	Energies 10.3390/en16031251	operative temperature; passive design; school building; simulation; thermal comfort; thermal environment
[42] Haddad S.; Synnefa A.; Ángel Padilla Marcos M.; Paolini R.; Delrue S.; Prasad D.; Santamouris M.	2021	On the potential of demand-controlled ventilation system to enhance indoor air quality and thermal condition in Australian school classrooms	Energy and Buildings 10.1016/j.enbuild.2021.110838	air quality; indoor environmental quality; school buildings; thermal comfort; ventilation
[44] Kapoor N.R.; Kumar A.; Alam T.; Kumar A.; Kulkarni K.S.; Blecich P.	2021	A review on indoor environment quality of Indian school classrooms	Sustainability (Switzerland) 10.3390/su132111855	acoustic comfort; artificial intelligence; classroom; COVID-19; indoor air pollution; indoor air quality; sick building syndrome; thermal comfort; ventilation; visual comfort
[45] Lala B.; Kala S.M.; Rastogi A.; Dahiya K.; Yamaguchi H.; Hagishima A.	2022	Building Matters: Spatial Variability in Machine Learning Based Thermal Comfort Prediction in Winters	Proceedings—2022 IEEE International Conference on Smart Computing, SMARTCOMP 2022 10.1109/SMARTCOMP55677.2022.00078	classrooms; energy efficiency; IoT; machine learning; multi-class classification; natural ventilation; sensors; spatial variability; students; thermal comfort
[37] Peters T.; D'Penna K.	2020	Biophilic design for restorative university learning environments: A critical review of literature and design recommendations	Sustainability (Switzerland) 10.3390/su12177064	critical analysis; design method; education; learning; literature review; questionnaire survey; student; university sector
[38] Suradhuhita P.P.; Setyowati E.; Prianto E.	2022	Influence of a facade design on thermal and visual comfort in an elementary school classroom	IOP Conference Series: Earth and Environmental Science 10.1088/1755-1315/1007/1/012013	not provided
[43] Mazlan A.N.; Saad S.; Yahya K.; Haron Z.; Abang Hasbollah D.Z.; Kasiman E.H.; Rahim N.A.; Salehudddin A.M.	2020	Thermal comfort study for classroom in urban and rural schools in Selangor	IOP Conference Series: Materials Science and Engineering 10.1088/1757-899X/849/1/012016	not provided

Table 2. *Cont.*

Authors	Year	Title	Journal DOI	Keywords
[46] Lan K.; Chen Y.	2022	Air Quality and Thermal Environment of Primary School Classrooms with Sustainable Structures in Northern Shaanxi, China: A Numerical Study	Sustainability (Switzerland) 10.3390/su141912039	air quality; classroom; numerical simulation; sustainable building; thermal environment
[39] Talarosha B.; Satwiko P.; Aulia D.N.	2020	Air temperature and CO_2 concentration in naturally ventilated classrooms in hot and humid tropical climate	IOP Conference Series: Earth and Environmental Science 10.1088/1755-1315/402/1/012008	ASHRAE; CO_2 concentration; comfort temperature; natural ventilation; school classroom
[47] Chang L.-Y.; Chang T.-B.	2023	Air Conditioning Operation Strategies for Comfort and Indoor Air Quality in Taiwan's Elementary Schools	Energies 10.3390/en16052493	air-conditioning; elementary school; IAQ; thermal comfort; ventilation
[49] Tagliabue L.C.; Accardo D.; Kontoleon K.J.; Ciribini A.L.C.	2020	Indoor comfort conditions assessment in educational buildings with respect to adaptive comfort standards in European climate zones	IOP Conference Series: Earth and Environmental Science 10.1088/1755-1315/410/1/012094	adaptive comfort standards; climate zone; educational buildings; indoor comfort conditions
[51] Fabozzi M.; Dama A.	2020	Field study on thermal comfort in naturally ventilated and air-conditioned university classrooms	Indoor and Built Environment 10.1177/1420326X19887481	adaptive model; fanger model; field study; gender; natural ventilation; thermal comfort
[52] López-Chao V.; Lorenzo A.A.; Saorín J.L.; De La Torre-Cantero J.; Melián-Díaz D.	2020	Classroom indoor environment assessment through architectural analysis for the design of efficient schools	Sustainability (Switzerland) 10.3390/su12052020	acoustics; environmental quality; learning space; occupant comfort; sustainable architecture; sustainable building; thermal comfort; ventilation comfort; visual comfort
[50] Grassie D.; Karakas F.; Schwartz Y.; Dong J.; Milner J.; Chalabi Z.; Mavrogianni A.; Mumovic D.	2022	Modelling UK school performance by coupling building simulation and multi-criteria decision analysis	17th International Conference on Indoor Air Quality and Climate, INDOOR AIR 2022	building simulation; cognitive performance; decision analysis; indoor air quality; school buildings; thermal comfort
[53] Sadrizadeh S.; Yao R.; Yuan F.; Awbi H.; Bahnfleth W.; Bi Y.; Cao G.; Croitoru C.; de Dear R.; Haghighat F.; Kumar P.; Malayeri M.; Nasiri F.; Ruud M.; Sadeghian P.; Wargocki P.; Xiong J.; Yu W.; Li B.	2022	Indoor air quality and health in schools: A critical review for developing the roadmap for the future school environment	Journal of Building Engineering 10.1016/j.jobe.2022.104908	classroom air quality; energy use in schools; exposure risk; particle matter; ventilation; volatile organic compounds
[48] Catalina T.; Damian A.; Vartires A.; Nița M.; Racovițeanu V.	2023	Long-term analysis of indoor air quality and thermal comfort in a public school	IOP Conference Series: Earth and Environmental Science 10.1088/1755-1315/1185/1/012008	not provided

A review of the current literature on thermal comfort and students' ability to learn showed that there is no universal range of comfort temperature for all schools, as this temperature depends on the location of the building (rural/urban) and climatic zone. Pupils and teachers need about a week to adapt to the conditions in the school.

There is a direct relationship between ventilation, the size of the room, the view from the window, and attachment to the place occupied in the classroom and the student's performance. In addition to the air parameters, the environment also has an impact on the ability to learn: colors, the presence of plants, natural lighting, or the ability to open a window to take advantage of natural ventilation.

Children have difficulty in determining their thermal preferences and the level of thermal comfort but can assess their thermal sensations.

5. Thermal Comfort in Terms of Ventilation of Hospital Buildings

Hospital facilities are a category of buildings in which ventilation affects the feeling of thermal comfort and is particularly important from the point of view of hygienic safety: airborne disease transmission. The users of such facilities are people with special thermal requirements—sick people, people with impaired functions of the immune system, those undergoing convalescence, generally weakened people, and those representing a rather limited level of physical activity. On the other hand, hospitals employ staff who perform intense physical and/or intellectual work, are on the move (showing a high level of physical activity), and stay in the same rooms as patients. Expectations of these two groups, patients and personnel, regarding thermal parameters in rooms, are therefore divergent. The above-described aspects related to the ventilation of hospital rooms mean that they are still the subject of research and analysis, the latest of which is discussed in this chapter.

In the years 2020–2023, six review papers were published on the subject of hospital ventilation and thermal comfort, which were searched in the Scopus database by entering the phrase: "thermal comfort ventilation hospitals review". Two papers from the search results were excluded due to being less related to the subject of this review: "Engineering solutions for preventing airborne transmission in hospitals with resource limitation and demand surge" and "Biophilic design for restorative university learning environments: A critical review of literature and design recommendations".

In the review paper [54], hospitals are presented in the introduction as particularly energy-consuming in the comparison to other types of buildings. The main reason for this situation is the nature of the use of hospitals: 24/7 use as well as the constant need to use artificial lighting and technological processes. An interesting comparison was made in the context of average annual electric and thermal energy consumption per gross floor area, presented in Table 3.

Table 3. Electric and thermal energy consumption per gross floor area in various countries, based on [54].

Country	Electric Energy [kWh/m^2]	Thermal Energy [kWh/m^2]
Switzerland (CH)	75	195
Belgium (BE)	80	275
Netherlands (NL)	80	320
Sweden (SE)	100	175
United Kingdom (UK)	110	500
Greece (GR)	115	300
Austria (AU)	180	210
Unated States (US)	240	700
Canada (CA)	340	720

The high demand for both heat and electricity causes great interest in the possibility of reducing energy consumption in hospitals. The authors of the review [54] refer to studies that show that the very structure of the ventilation system can significantly affect both energy consumption and comfort, and that there are solutions that are beneficial in both respects: "when exhaust opening was set at the ceiling level (rear-middle-level)". In the conclusions, the authors point to the possibility of saving energy through the use of energy-saving ventilation control systems, which is also indicated by the authors of the review on ventilation systems in general [1] or the work comparing the operation of earth-to-air heat exchangers operating according to different schedules of use [10] (adapting to user needs).

Operating theaters are special rooms in hospital buildings, to which separate studies are devoted. The specificity of technical equipment systems in operating rooms reflects the specific technological needs of various categories of procedures and the risk of infection (from the operated patient or from the patient). An overview of ventilation systems in operating theaters only was published in [55] in 2021. In the highlights of the paper, the authors point out that the cleanliness and hygienic safety of the surgical zone is mainly due to adequate ventilation. At the same time, they note that the choice of the ventilation system is ambiguous and, despite many studies, it remains controversial. The problem related to the ventilation of operating rooms in the context of thermal comfort, already mentioned in the introduction, is the discrepancy between the needs of the staff and the patient—the first group expects a lower temperature for the comfort of intensive work, and the patient should not become too cold during the procedure when he lies still without clothes in a state of complete anesthesia. For this reason, surgical staff and HVAC engineers should cooperate and mutual understanding between them seems to be crucial, which indicates that a lot in promoting the knowledge is waiting to do it. In the conclusions, the following issues were raised as key in the context of ventilation systems:

(a) Design of the surgical lamp that will not block the air supply to the operation zone or cause air recirculation under the lamp;
(b) Broad laminar air flow diffusers play a great role in reducing the sensitivity of the laminar ventilation system to door opening;
(c) The use of an appropriate personnel dressing system may, on the one hand, reduce contamination from clothing, and at the same time serve to achieve a compromise in terms of thermal comfort of the surgical staff vs. the patient.

A review of works on thermal comfort in naturally ventilated patient rooms in the tropics is presented in [56]. The authors argue that natural ventilation is a solution that can provide adequate airflows in a tropical climate and provide thermal comfort at a low financial cost. Maintaining the proper air flow can be supported by additional devices and controlled by BMS (building management system) automation systems. The article points out that the thermal comfort of patients depends to a large extent on their health and many other factors, citing research conducted in a tropical climate. At the same time, research results have been found which show that in this climate, hospital staff experience discomfort more often than patients. The authors put emphasis on the review of works on the use of heat pumps and photovoltaic panels to power systems for maintaining thermal comfort in a building, including ventilation. In their conclusions, they concluded that this combination may be the answer to the need to ensure comfort with a high potential for energy savings, resulting from the high coefficient of performance of heat pumps (COP = 6.14) and the use of solar radiation as a renewable energy source, thanks to which photovoltaic (PV) panels produce electricity for heat pump power supply.

Studies of thermal comfort in naturally ventilated patient rooms in the tropics are described in [57] by an extended group of authors from [56]. Comfort was assessed using simulation, in situ measurements and field survey in Kepala Batas Hospital (Malaysia). One can read in the paper that "simulation results presented that more than half of the total occupants in the ward feel discomfort, with a predicted mean vote (PMV) between 1.0 and 1.6 and a predicted percentage of dissatisfied between 40% and 56%". The results of the simulations carried out in the work were consistent with the results obtained on the basis of measurements but differed from the questionnaire survey. Significantly more people voted that the conditions in the sick room are uncomfortable. The authors indicate that this may be due to a variety of diseases. For example, chronically ill patients with "Alzheimer's disease, Parkinson's disease, cardiovascular disease, diabetes, respiratory problems and kidney disease, are the most susceptible to heat". The results presented in the paper also showed that "people in a tropical climate zone are well accustomed to hot-humid weather and would tolerate high temperatures".

The last of the discussed review articles [58] comes from 2022 and is the most comprehensive knowledge base on past research in the field of thermal comfort, ventilation, and energy efficiency in hospital rooms. The article reviews the field-surveys of thermal comfort, indicating the methods used in individual studies and characterizing the group of respondents (e.g., patients, staff, staff and patients, pregnant women, etc.). The authors point out that a large number of works in the literature concern hypothermia as one of the most important consequences of the lack of thermal comfort and poorly designed/maintained HVAC systems. They cite the results of research in which an attempt was made to separate comfort zones—separate for the patient and staff—using a nozzle (a type of air curtain). The review concludes with the authors' thoughts on key themes that present major challenges today:

- Continuation of the study of factors inside and outside the building affecting the thermal comfort of users;
- Adjusting the temperature in the room to the condition of patients and the type of diseases, as well as research on adaptive thermal comfort in hospitals;
- The use of "self-warming blankets, prototype thermal compression devices, and in-line intravenous fluid warming" to improve the patient's thermal comfort during surgery while maintaining the thermal comfort of surgeons;
- Refining the guidelines regarding the time needed to achieve full functionality of operating rooms for various ventilation systems—so as to be able to save energy without sacrificing air quality and thermal comfort.

Table 4 presents list of discussed review publications in the field of thermal comfort and ventilation in hospitals.

Table 4. List of discussed review publications in the field of thermal comfort and ventilation in hospitals.

Authors	Year	Title	Journal DOI	Keywords
[54] Anwer A. Gatea et al.	2020	Energy Efficiency and Thermal Comfort in Hospital Buildings: A Review	International Journal of Integrated Engineering 10.30880/ijie.2020.12.03.005	Energy efficient, hospital, thermal comfort
[55] Sasan Sadrizadeh et al.	2021	A systematic review of operating room ventilation	Journal of Building Engineering 10.1016/j.jobe.2021.102693	Hospital operating room, indoor air quality, thermal comfort, infection control, surgical clothing system, source strength
[56] Abd Rahman et al.	2021	A Literature Review of Naturally Ventilated Public Hospital Wards in Tropical Climate Countries for Thermal Comfort and Energy Saving Improvements	Energies 10.3390/en14020435	thermal comfort; building energy; naturally ventilated ward; hybrid system; tropical climate
[58] Feng Yuan et al.	2022	Thermal comfort in hospital buildings—A literature review	Journal of Building Engineering 10.1016/j.jobe.2021.103463	Thermal comfort, hospital buildings, improvement measures, energy efficiency

Paper [59] presents the investigations of temperature, relative humidity, and carbon dioxide in four hospitals in Pakistan. Four types of rooms were assessed in every hospital: emergency room, operation room, intensive care unit, and medical ward. "The results show that occupancy rate, ambient thermal conditions, type of HVAC system, and building orientation are vital drivers of IEQ".

In the paper [60], the temperature and humidity in the operation rooms were investigated for (i) "conventional heating, ventilation, and air conditioning system" (ii) "liquid desiccant air conditioning (LDAC) system", and (iii) rotary desiccant air conditioning (RDAC) systems. The energy usage was monitored in parallel with airborne bacterial concentrations. The humidity for conventional, LDAC, and RDAC systems was respectively 66.7%, 60.8%, and 60.5%, while energy consumption was 14.1 kWh/m^2, 11.8 kWh/m^2, and 10.1 kWh/m^2, indicating RDAC as an energy-efficient and preferable system.

In [61], the following parameters were investigated in the newly built hospital in Bristol (United Kingdom): "temperature, RH, CO_2, particulate matter (PM2.5, PM10), and NO_2" and concentration levels of benzene, formaldehyde, and trichloroethylene. User surveys were used to assess lighting and acoustics comfort. The presented results show that mechanical ventilation ensures satisfactory air quality in the tested building; however, the authors of the article point to the possibility of improving the energy efficiency of the system, the possibility of an energy audit thanks to the BMS (building management system) technology and present suggestions for improving air quality and thermal comfort in rooms existing in hospitals and also pay attention to aspects that may be useful in the case of designing new buildings—e.g., to ensure adequate filtration.

The article [62] presents multi-criteria methods for assessing the suitability of a given ventilation system in an operating room. This method is based on the "analytic hierarchy process and fuzzy comprehensive evaluation", which takes into account seven parameters in the context of the three evaluation criteria "ventilation effectiveness, energy consumption and users' satisfaction". The proposed method was verified during a simulated operation in two rooms in St. Olavs Hospital in Norway, which were equipped with different ventilation systems: laminar or mixing. During the pilot tests, the laminar system obtained an acceptable result, and the mixing system an inadequate one. The authors suggest that this assessment method can be used during commissioning of operating rooms in order to verify the achievement of both comfort and energy efficiency parameters.

The adaptive comfort model was the subject of research described in the article [63] for nursing homes. In order to verify its applicability, surveys were conducted in five nursing homes in Spain (Mediterranean climate). The results showed that in the case of naturally ventilated rooms, the inhabitants presented a greater ability to adapt, understood as tolerance to comfort parameters deviating from the desired ones. This observation led to the conclusion that the use of natural ventilation without air conditioning can reduce energy consumption without significantly affecting the thermal comfort of residents. At the same time, the research confirmed that the ASHRAE 55:2020 thermal comfort model can be considered as close to the expectations of nursing home residents. Such dependence was not obtained for non-residents—service employees. Studying a larger group of these people is the goal of further studies planned in the future.

Parameters in the operating room: predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) were investigated by means of CFD simulation in [64]. The influence of air inlet temperature on the flow pattern and thus on the thermal comfort sensation was investigated. The results show that a temperature of about 18 °C is needed. Nevertheless, in the analyzed cases, the recirculation zones which can be repaired with usage of some air curtains occurred, but it was not simulated in the paper.

Table 5 presents a list of publications on thermal comfort and ventilation in hospitals.

Table 5. List of other publications on ventilation and thermal comfort in hospitals.

Authors	Year	Title	Journal DOI	Keywords
[57] Abd Rahman, Noor Muhammad et al.	2021	Thermal comfort assessment of naturally ventilated public hospital wards in the tropics	Building and Environment 10.1016/j.buildenv.2021.108480	naturally ventilated ward, public hospital, thermal comfort tropical climate
[59] Khan M. et al.	2020	Thermal comfort and ventilation conditions in healthcare facilities—Part 1: An assessment of indoor environmental quality (IEQ)	Environmental Engineering and Management Journal 10.30638/eemj.2020.087	CO_2 concentration; healthcare facilities; HVAC system; indoor environmental quality; thermal comfort
[60] Tsung-Yi Chien et al.	2020	Comparative Analysis of Energy Consumption, Indoor Thermal–Hygrometric Conditions, and Air Quality for HVAC, LDAC, and RDAC Systems Used in Operating Rooms	Applied Sciences 10.3390/app10113721	dehumidification air conditioning system; humidity; energy consumption; air quality; operating room; ventilation
[61] Nishesh Jain e tal.	2021	Building Performance Evaluation of a New Hospital Building in the UK: Balancing Indoor Environmental Quality and Energy Performance	Atmosphere 10.3390/atmos12010115	building performance evaluation; indoor environmental quality (IEQ); indoor air quality (IAQ); energy performance; hospitals
[62] Fan, Minchao et al.	2021	Suitability evaluation on laminar airflow and mixing airflow distribution strategies in operating rooms: A case study at St. Olavs Hospital	Building and Environment 10.1016/j.buildenv.2021.107677	air distribution strategy, operating room suitability evaluation
[63] N. Forcada et al.	2021	Field study on adaptive thermal comfort models for nursing homes in the Mediterranean climate	Energy and Buildings 10.1016/j.enbuild.2021.111475	adaptive thermal comfort model, nursing homes, elderly, naturally ventilated, air-conditioned, thermal comfort standards
[64] Gutierrez, Albio D. et al.	2022	Required thermal comfort conditions inside hospital operating rooms (ORS): a numerical assessment	Frontiers in Heat and Mass Transfer 10.5098/hmt.18.4	computational fluid dynamics (CFD); heat, ventilation, and air conditioning (HVAC); indoor environmental quality (IEQ); operating rooms (ORs); thermal comfort

A review of recent articles on ventilation in the context of thermal comfort did not show clear trends. Various areas of research are constantly assessed: from the issue of air distribution through methods of heat and moisture recovery and methods of controlling the operation of the system to the quality of filtration (PM2.5 PM10) or the issues of adaptive comfort of patients and hospital staff as two groups with opposite expectations. Access to real operating rooms for research purposes is limited, and the results are “sensitive”. For these reasons, it can be expected that the works found in the literature do not fully reflect all activities that are taking place in this field in the world.

6. Thermal Comfort, Ventilation, and Quality of Sleep

People spend about one-third of their lives sleeping. Therefore, it is extremely important to provide a suitable indoor environment in bedrooms. The appropriate indoor environment consists of air quality, thermal comfort, and acoustic comfort. Research on the indoor environment in bedrooms focuses on these three aspects. The researchers consider the evaluation of indoor air quality and its relationship to room ventilation, thermal comfort, or acoustic comfort, with the inclusion of sleep quality measurements in addition to measuring these elements of the indoor environment.

Between 2020 and 2023, according to the Scopus database, with the search criteria selected for this review (title, abstract, or keywords including "thermal" and "comfort" and "ventilation" and "sleep quality"), 12 original studies were found and reviewed in this section.

Studies conducted in Africa focused on evaluating the feasibility of retrofitting buildings to reduce the spread of malaria [65]. At the same time, thermal comfort during the night was noted as an important factor for a good night's sleep. Special attention should be paid to this aspect. The authors recommended the introduction of increased airflow through buildings, i.e., an increase in the exchange of air. The analysis covered buildings in the Gambia—a traditional building with leaks at the junction of the roof and external walls, as well as more modern buildings with metal roofs with tight construction. Due to the construction of houses characterized by low airtightness, the authors were unable to assess ventilation using a typical blower door test. The effectiveness of ventilation was assessed by measuring carbon dioxide concentrations in a traditional (less airtight), and a modern building was analyzed. It was estimated that in the case of houses located in Africa, it is essential to provide airflow through which pollutants can be diluted, which reduces the risk of contracting malaria but also improves thermal comfort. Thermal comfort is influenced by the speed of air movement. By creating additional openings in buildings or introducing additional windows, the authors obtained a greater multiplicity of air exchanges. The study also concluded that for old-type buildings or traditional houses, the African method of assessing ventilation by measuring carbon dioxide concentrations could give good results. This is a certain indication that can be used to assess the indoor environment of existing buildings, especially leaky ones.

For the authors of [65], it was also important to draw attention to the fact that the analysis of thermal comfort to ensure appropriate conditions, especially for falling asleep, is often discussed while the importance of ventilation and air movement is omitted. Similar conclusions were reached by other authors of [66], who studied ventilation scenarios for tiny sleeping spaces. Tiny sleeping spaces are increasingly popular spaces that can be found in the form of capsule hotels, sleeping boxes, or sleeper compartments. The influence of air velocity in the capsule on the feeling of comfort was analyzed. Scenario 1 included the air velocity in the capsule in the range of 0.1 to 0.24 m/s and the provision of conditions in which the PMV would be between −0.5 and +0.5. In Scenario 2, the minimum amount of air was introduced and the speed was significantly higher (0.5 m/s). In Scenario 3, the DR value was limited to 5.3% to reduce the draught. The authors evaluated the effects of temperature and air movement in the capsule. They showed that it is more important to ensure adequate air exchange than to focus on the temperature of the supply air. The most comfortable conditions were obtained for Scenario 1. It is recommended to use air exchange in the sleeping environment in such a way that there is air movement but in the range of up to 0.24 m/s.

Analyses in the summer using a climate chamber were carried out in China [67]. The authors examined the sleep of 24 people and the influence of changing climatic conditions in terms of air temperature (28/30/32 °C), relative humidity (50/80%), and air velocity (0.39/0.69/1.17 m/s). Sleep was assessed using the Fitbit app, which records the duration of different phases of sleep. Analysis of the results showed that in the case of climatic comfort during sleep, the air movement is important, due to which even at higher air temperature and higher humidity a favorable PMV range can be obtained. At air temperature above

32 °C, the movement of air does not cause a feeling of comfort. It was estimated that feelings of comfort may be related to sleep phases, as it was noticed that the surface temperature of the skin varies before falling asleep, during sleep, and after waking up. The authors also carried out an energy assessment, indicating that obtaining high air velocities can cause increased electricity consumption. Therefore, they recommend considering the introduction of local elements in bedrooms that force air movement without the need to cool it. This can contribute to reducing the energy demand for air conditioning systems.

In Denmark [68], surveys were carried out in which information was collected on the configuration of bedrooms and the ventilation systems in which the buildings are equipped. Information was collected from 517 people. Questions were asked about room ventilation, how the air is supplied, the location of the building and bedroom, noise and the thermal environment. Sleep was assessed using the Pittsburg Sleep Quality Index (PSQI). Surveys have shown that only 33% of bedrooms are equipped with mechanical ventilation, 14% with exhaust air systems, and the rest are naturally ventilated. Respondents also rated disturbance and the largest resulted from the lack of mechanical ventilation, the presence of carpets, and feelings heat. People who felt the thermal environment was too hot were more likely to ventilate rooms during the day and before bedtime. The results showed that there is a link between ventilation and the feeling of thermal comfort and that people who experience discomfort try to remedy this by ventilating rooms. The authors also pointed out that field studies are necessary to link people's feelings with objective measurement results.

Subjective surveys and measurements were also conducted in China among students living in dormitories [69]. The survey asked about their own feelings about thermal comfort, humidity environment, acoustic environment, indoor air quality, and satisfaction level. Each answer was assigned points on a scale of −3 to +3. From cold/very poor/very noisy/very dry/very satisfied with −3 to extremely different answers with +3 (hot/very humid/very quiet/very good/very satisfied). Temperature, relative humidity, the concentration of carbon dioxide and particulate matter, formaldehyde concentration, and noise were also measured. Measurements were taken for one month in two small bedrooms with four beds. The authors found a correlation between survey responses and measured air parameter values. The air temperature was 26–28 °C, which significantly exceeds the comfort values by 4–5 °C. Relative humidity was about 40% and was at an acceptable level. In turn, the CO_2 concentration on average was about 4000 ppm, which means that air quality was very poor. The authors assessed the internal environment is uncomfortable and does not meet commonly accepted values that indicate appropriate conditions. The students in their survey responses also described the prevailing conditions as unsatisfactory, which only confirmed the measured values. Although the study was conducted in a short period of time and only in two bedrooms, the authors indicate further research directions, which should include a larger number of subjects. They decided that the results could help implement the guidelines for dorm users: ventilate frequently, especially before bedtime, lower the temperature with local devices, and use earplugs.

In Romania [70], tests of CO_2 concentration in the bedrooms of buildings that had been refurbished 2 years earlier were undertaken. Measurements of the CO_2 concentration were carried out in three rooms with natural ventilation. The concentration of CO_2 after 8 h of sleep reached values of up to 5680 ppm (when two people slept in the bedroom). This is a very high value that should not occur in any room where people are. Spending time in rooms with such high concentration can negatively affect not only the quality of sleep but even health. The authors noted that the bedrooms were aired before bedtime, but due to the significant increase in CO_2 concentration, this was ineffective. Additionally, the authors estimated that in winter, airing the room for 10 min causes a decrease in internal temperature by 3.3 °C (at an outside air temperature of 1.5 °C), so it is disadvantageous due to energy consumption for heating. The authors recommend the use of sensor-controlled mechanical ventilation in bedrooms.

The problem of heating costs, in terms of providing comfortable conditions in bedrooms, was raised in research in New Zealand [71]. The authors conducted a long-term study evaluating thermal comfort in children's bedrooms. They estimated that more than 50% of children sleep in uncomfortable conditions, which in these studies were determined by low indoor air temperatures. They identified that the reason for this condition is poor insulation of external partitions, insufficient ventilation, and lack of financial resources for heating buildings. They proposed to use a heat pump for heating. At the same time, they assumed that there should be good air quality in bedrooms, determined by the concentration of PM2.5. They ran CFD simulations that included the introduction of ventilation into bedrooms, assumed indoor temperatures, and determined PMV and PPD. In their conclusions, they stated that it is possible to achieve thermal comfort (PMV index of 0.72) when the set temperature is 22 °C. Research was carried out in the first weeks of winter. An interesting observation, which required further research, was the assessment that at the temperature of 19 °C in the second month of the study, when the energy consumption for heating was higher than at a temperature of 22 °C. The authors assessed that this was due to the higher humidity of the outside air.

Research on thermal comfort during sleep, in connection with ventilation, was conducted by authors from China [72]. They assessed that the bedrooms are heated in different ways: radiation, ceiling heating, wall heating, and others. The distribution of heating affects the formation of zones with different parameters, which can affect the feeling of comfort during sleep. The authors proposed a combination of heating and ventilation systems, stratum ventilation heating, thanks to which comfortable conditions can be obtained. This system is characterized by blowing air from the side of the head of a sleeping person. The temperature distribution in this system ensures appropriate thermal conditions. Thanks to this system, it is also possible to maintain adequate air quality. By preparing the right amount of air, this system is energy efficient. Further research by the same authors [73] concerned a more accurate assessment of air distribution in bedrooms using the aforementioned stratum ventilation system and mechanical mixing ventilation. The stratum system is recommended because by supplying air to the zone occupied by people, with the same value of the PMV comfort index, 10% energy savings can be achieved.

The definition of a ventilation strategy for bedrooms in single-family buildings was carried out in research on the characteristics of naturally ventilated and mechanically ventilated apartments [74]. CO_2 concentrations and air exchange rates were assessed in nine variants, including bedroom door/open, natural/mechanical ventilation, and various combinations of these cases. Due to a series of many measurements, the authors found that when the bedroom has natural ventilation, its door should be open during sleep. An even better effect can be achieved when a mechanical air extraction is used simultaneously with the door open (e.g., in the kitchen). In the case of mechanical ventilation, it was determined that air exchange with a multiplicity of 0.6 h^{-1} allowed maintaining of the CO_2 concentration below 1000 ppm. The authors also determined the CO_2 emission of a sleeping person at the level of 7.9–10.9 L/h, which is less than the standards (12.8–13.9 L/h). The authors assessed that in terms of thermal comfort, both in the case of natural and mechanical ventilation, conditions within the recommended values were obtained.

Table 6 presents a list of publications in the field of thermal comfort, ventilation in bedrooms with regard to sleep quality.

Table 6. List of discussed review publications in the field of thermal comfort and ventilation in bedrooms.

Authors	Year	Title	Journal DOI	Keywords
[67] Chenqiu Du et. al.	2022	A model developed to predict thermal comfort during sleep in response to appropriate air velocity in warm environments	Building and Environment 10.1016/j.buildenv.2022.109478	sleep quality; thermal comfort; warm environment; appropriate air velocity; prediction model
[69] Dan Mio et al.	2022	Associations of indoor environmental quality parameters with students' perceptions in undergraduate dormitories: a field study in Beijing during a transition season	International Journal of Environmental Research and Public Health 10.3390/ijerph192416997	dormitory; indoor environmental quality; indoor air quality; noise; carbon dioxide; well-being
[66] Haiguo Yin et al.	2020	Performance evaluation of three attached ventilation scenarios for tiny sleeping spaces	Building and Environment 10.1016/j.buildenv.2020.107363	tiny sleeping spaces; sleepin environment; double side-attached ventilation; air quality
[68] Chenxi Liao et al.	2021	A survey of bedroom ventilation types and the subjective sleep quality associated with them in Danish housing	Science of the Total Environment 10.1016/j.scitotenv.2021.149209	not provided
[65] Jakob B. Knudsen et al.	2020	Measuring ventilation in different typologies of rural Gambian houses: a pilot experimental study	Malaria Journal 10.1186/S12936-020-03327-0	airflow; housing, malaria; the Gambia
[72] Jian Liu and Zhang Lin	2020	Performance of stratum ventilated heating for sleeping environment	Building and Environment 10.1016/j.buildenv.2020.107072	heating; sleeping environment; horizontal temperature distribution; stratum ventilation; operative temperature
[73] Jian Liu and Zhang Lin	2020	Energy and exergy analyses of different air distribution in residential buildings	Energy and Buildings 10.1016/j.enbuild.2020.110694	sleeping environment; air distribution; stratum ventilation; energy and exergy analysis; computational fluid dynamics
[71] Mohammad Al-Rawi	2021	The thermal comfort sweet-spot: A case study in residential house in Waikato, New Zealand	Case Studies in Thermal Engineering 10.1016/j.csite.2021.101530	indoor environmental quality; computational fluid dynamics; Waikato; New Zealand
[70] D.A. Adincu et al.	2020	Experimental measurements of CO_2 concentrations in sleeping rooms	IOP Conference Series: Materials Science and Engineering 10.1088/1757-899X/997/1/012137	not provided
[74] Chandra Sekhar et al.	2020	Detailed characterization of bedroom ventilation during heating season in a naturally ventilated semi-detached house and a mechanically ventilated apartment	Science and Technology for the Build Environment 10.1080/23744731.2020.1845019	not provided

Paper [75], although meeting the search criteria, was not included in the review because it did not address the subject of sleep quality or bedroom issues. The study looked at thermal comfort in dormitories, and the recommendations were about thermal comfort during the day rather than at night. Also not included is [76], which is an article that was a review of research in Indonesia.

Sleep quality can be defined in different ways. The lengths of individual sleep phases are assessed or other indicators are used, e.g., the Pittsburg Sleep Quality Index (PSQI). Although there are no strict norms or guidelines for sleep quality, by analyzing these selected methods, it is possible to conclude whether sleep was valuable. Other methods of assessing sleep quality are conducting survey. Although these are rather subjective studies, taking into account the objective measurements of various parameters, scientists conclude about the impact of selected factors on people's feelings. In the analyzed works, the research was conducted in different groups of people (children, students) and different types of sleeping rooms (dormitories, tiny sleeping spaces and residential buildings). The choice of parameters to assess thermal comfort, ventilation, or air quality parameters, as well as the assessment of the impact of other factors that may affect the quality of sleep in bedrooms, depends on the location of the building and local conditions, as well as the season or the way the bedroom is used. The research was conducted in China, Denmark, Romania, New Zealand, and the Gambia. Because sleep is one of the elements of everyday life, its quality may be influenced not only by ventilation and thermal sensations, which should be borne in mind when analyzing the results.

7. Ventilation Impact on Thermal Comfort of Atrium Buildings

A modern atrium is a covered space surrounded by a building, usually equipped with a glazed roof, skylights, or large windows. The atrium can significantly improve building occupants' comfort due to providing a large common space and additional daylight, giving an impression of a connection with an exterior environment. However, the thermal comfort of the atrium space depends on many factors, including interaction with solar radiation and thermal buoyancy forces related to the height of the space. Proper ventilation can significantly affect thermal comfort by providing comfortable air temperature and velocity in the occupied zone, dissipating solar heat gains in the summer, and influencing the air temperature gradient. In addition, as the atrium can impact the energy balance of the building significantly, the optimal ventilation strategy can improve energy performance and thermal comfort in the atrium. Aspects related to atrium ventilation and thermal comfort are still the subject of recent research.

From January 2020 to May 2023, according to the Scopus database, with the search criteria selected for this review (title, abstract, or keywords including "thermal" and "comfort" and "ventilation" and ("atrium" or "atria")), no review papers were published, but 14 original studies were found. These studies are reviewed in this paper.

The paper [77] presents the investigation of energy performance and thermal comfort of the atrium. It is found that geometric parameters, especially height, presence and location of the platform, shape, and opaque-to-transparent surfaces are the most important factors. The research was conducted for the winter and summer in the atrium of a hotel located in China. Orthogonal experiments and CFD simulations were conducted. Although the energy aspect is the main focus of this research, some conclusions are drawn regarding thermal comfort and ventilation, i.e., the presence of the platform significantly impacts the thermal environment of the space under it. The platform shields the floor from solar radiation in the summer, stabilizes and unifies the temperature distribution in winter, and forces the ventilation air under the platform to flow with a cross path, which allows for maintaining better thermal comfort under the platform.

Winter thermal characteristic of the central atrium with skylights is studied in [78] for a teaching building in the cold climate of China. Field measurements of indoor thermal environment parameters (i.e., air temperature, humidity, atmospheric pressure, PMV, PPD) and occupants' thermal comfort rate questionnaire survey were implemented. An analysis of vertical and horizontal temperature distribution was conducted with the use of measurement instruments such as a thermal infrared imager, and illuminance UV recorder. It was proved, that the atrium thermal environment was affected by the fenestration airtightness, chimney effect, and skylight radiation. Based on the results of 70 surveys on thermal comfort, the formula was developed, describing the measured thermal sensation and PMV index as a function of operative temperature. Furthermore, it was concluded that the measured neutral temperature is lower than predicted with the Fanger model (about 17 °C in comparison to about 18.4 °C, respectively), and the measured comfort temperature range is wide, ranging from about 13 °C to about 21 °C. The formula for temperature in the atrium as a function of altitude was proposed. As the wide indoor air temperature range (reaching over 8 °C) impacted occupants' rating for thermal comfort, some solutions for improving thermal comfort were proposed, i.e., floor heating and cross ventilation, to provide more heterogeneous indoor thermal conditions.

Paper [79] is an analysis of various design parameters of the atrium in a commercial building on thermal comfort, daylighting, and natural ventilation. A central atrium was assessed with a field study, and a quantitative analysis was conducted to study the importance of various natural ventilation and daylighting strategies related to thermal comfort. The window-to-wall ratio and the glazing type were selected as parameters impacting the thermal comfort and daylighting the most. It was concluded that the natural ventilation, if designed optimally, can significantly decrease the energy consumption of the building. The window opening area and schedule are the most important design parameters.

An effect of the atrium ceiling shape on catching sea breeze and its impact on indoor thermal comfort and natural ventilation is the purpose of an original study [80], conducted for a building located in Bushehr (Iran) with a BWh (hot and humid coastal) climate. A CFD simulation method with a model validated with empirical measurements in wind tunnels was implemented. Twelve shapes of the roof were simulated for reference summer conditions, and Fanger's PMV/PPD indexes were used to determine thermal comfort. The authors concluded that in a hot climate, an atrium should be designed with particular emphasis on natural ventilation to prevent overheating and to improve indoor thermal comfort. In the extensive literature review, the authors indicate examples of research on the positive impact of high air velocity (e.g., 3 m/s) on thermal comfort, as well as the impact of atrium geometry on the efficiency of natural ventilation and indoor temperature stratification. Some studies confirming the possibility of shape and opening optimization to increase the effectiveness of wind-assisted natural ventilation were listed, as well as studies describing the impact of various ventilation strategies (e.g., night cooling, the use of chimney draft, and solar chimneys) on thermal comfort in the atrium. The authors confirmed with their research that the appropriate shape of the atrium roof in windy areas (the indicated average wind speed in Bushehr is 5 m/s) can cause additional negative pressure at the opening, increasing the effectiveness of natural ventilation. A significant impact of the roof shape on the ventilation effectiveness and resulting thermal comfort was observed, with the PMV index ranging from +2.4 to +3.0.

The performance evaluation of a vertical linear supply slot diffuser in a ring-shaped atrium located in a building in Kuala Lumpur (Malaysia), shaded from solar radiation by surrounding, taller buildings is the purpose of the research paper [81]. The CFD simulation method was implemented with the Ansys Fluent software. The conducted research proved that the vertical linear supply diffusers with high capacity (about 450 $m^3/h/m$) and high supply air velocity (6.56 m/s) and located around the perimeter of the atrium at the low height (bottom level about 0.5 m above the floor) with exhaust grilles located under them can provide good airflow distribution, with a stratified thermal plume in the occupied, lower zone of the atrium. Acceptable thermal comfort was estimated for the supply diffusers located along the sidewalls of the atrium, according to calculated PMV and PPD indicators. It should be noted, however, that the presented results are adequate for atriums without the influence of solar radiation, which is typically an important factor determining airflow and thermal comfort in this type of space.

In [82], a study of energy and thermal characteristics of an atrium in a moderate climate of Poland is conducted. A large atrium with a glazed roof, giving a high glazed-to-opaque surface ratio, was studied in two variants, as a zone independent of the adjacent spaces and as a passive heater for fresh air for ventilation of adjacent spaces. Incorporating the atrium can significantly lower the use of artificial lighting in adjacent spaces and result in fewer hours of artificial lighting usage, which can reduce energy demand directly. In addition, reducing the time of use of built-in lighting impacts the HVAC systems' operational characteristics by lowering internal heat gains. The authors stated that the atrium makes it difficult to maintain the temperature in adjacent spaces in the comfortable range of 20–25 °C throughout the whole calendar year; however, in the case of the educational building unoccupied during the summer holiday, the comfortable temperature can be maintained for about 90% of the usage time. It was proved that the use of the atrium as a preliminary heat exchanger for fresh air for adjacent space ventilation can provide a comfortable temperature in the atrium's occupied zone (near the floor) but is related to the limitation of overheating the atrium in the summer.

Occupants' thermal comfort perception in two different, naturally ventilated central atrium spaces of public markets in Malaysia is the topic of research in [83]. This study included questionnaire surveys and field measurements of air temperature, humidity, and velocity. For the permanent occupants of the buildings (sellers), excessive temperature and humidity as well as excessively still air velocity were repeated feedbacks, and the use of individual mechanical fans or occupying zones with the best thermal conditions were the most common responses for the perceived thermal dissatisfaction. It was emphasized that there were ceiling fans located under the roofs of both atriums, which were unable to generate a perceptible air velocity in the occupied zone. The small sample size for the surveys should be noted (40 and 20 responders in both cases, respectively).

An open-plan, naturally ventilated multi-story office building with an atrium is studied in [84]. The CFD and WBM (water bath modeling) methods were used to examine ventilation efficiency reflected by the ACH (air changes per hour) factor and internal room air temperature above ambient. A total number of 36 cases varying in the design of the atrium, openings, and core configuration were examined, for which the abovementioned parameters were calculated for different floors of the building. According to the results, the ventilation efficiency is most sensitive to the opening design varying between 2.32 and 2.48 ACH for the mean floors, while the average horizontal thermal stratification is most sensitive to the atrium design, varying between 0.24 and 0.33 °C. The mean room air temperature above ambient at various office depths (locations between the external and atrium façade) also varies depending on the building configuration, which justifies the use of complex computational methods to predict airflow and thermal conditions in atrial buildings.

In [85], a multistory commercial building with a central atrium is studied. Thermal comfort in the atrium was to be provided by connection with neighboring mechanically air-conditioned office rooms, which allows hybrid ventilation of the atrium with the cooled air from the office rooms flowing through the public area to the atrium. The displacement and stack ventilation of the building were studied. The CFD simulation method was used to evaluate how external temperature, supply air inlet locations, flow paths between the atrium and surrounding public areas, ceiling height, and location of heat sources in offices affect the ventilation of the atrium. The PMV and PPD indices were used as a measure of thermal comfort. The authors found that displacement ventilation can be more effective than stack ventilation when the ambient temperature is high due to the impact of indoor–outdoor temperature difference on the pressure distribution. In high buildings with air intakes on each floor, reversed pressure distribution may occur in the upper floors that will cause the airflow from the atrium to the public area, which is a path opposite to the desired one. According to the results, this effect may happen when the ambient temperature is more than 3 °C higher than the indoor temperature, and the supply air is provided with inlets around the perimeter of the building. Ambient conditions have a limited effect on the indoor environment when fresh air is not provided by the external air intakes (i.e., displacement ventilation is designed instead of stack ventilation). The authors found that the air inlets between offices and public areas located at a low height provide better thermal comfort expressed in PMV than when the air inlets are located high (i.e., averaged PMV for supply air inlet at 0.4 m or 2.0 m above the floor was calculated as +1.13 and +1.34, respectively). Furthermore, the higher the handrails were (partitions between the atrium and surrounding public areas), the better averaged thermal comfort was noticed (i.e., resulting PMV was from +0.70 to +0.98 for handrail height of 1.9 m, and from +0.78 to +1.09 for 1.1 m). The combination of ceiling height, heat sources, and air inlets impact displacement ventilation system efficiency, and neutral PMV values can be achieved with a proper combination of the abovementioned parameters.

The paper [86] presents the CFD analysis of a subway station with the atrium space, ventilated using a piston ventilation pattern. As it is a specific case not related to typical buildings, this paper is not reviewed.

The paper [87] presents an analysis of cooling load reduction due to nighttime natural ventilation. A central atrium of a non-residential building, with an opaque roof and two exterior window facades on opposite sides of the building, equipped with a cooling floor, was studied to verify that opening opposite windows provide effective natural ventilation of the building and accumulation of cold in its thermal mass through the night, to be used during the day. The efficiency of nighttime precooling was simulated with the EnergyPlus model, while the CFD simulations with ANSYS Fluent were implemented to predict the wind-inducted pressure on the façade with window openings located near the floor on the windward side and near the roof on the leeward side to increase stack effect. The thermal and airflow dynamic models were validated by full-scale measurements. The authors determined that natural ventilation driven by stack and wind can be efficiently covered by modern simulation tools to predict night cooling potential. The potential of passive night cooling to reduce the daytime cooling load by about 27% in the hot climate of Portugal was proven, even with relatively small openings used (the total area of the operable windows in comparison to the floor area of the atrium was only about 1%). Thermal comfort was assessed with a set of surveys and indoor environmental parameters measured on two days with similar weather conditions. In the first case, only passive nighttime cooling was used, while additional active day cooling was implemented in the second. Air and mean radiant temperature, air speed, and relative humidity were measured, while about 30 occupants were asked to vote for their thermal sensation in both cases. According to the results, it was proved that nighttime natural cooling does not over-cool the building, has no negative effect on occupant's thermal sensation and allows the maintaining of good thermal comfort conditions without activation of the supplementary cooling floor system, as more than 80% of the occupants felt comfortable in that case, which is a decrement in comparison to the over 90% satisfied in the case of ventilation night cooling + day floor cooling case, but is still an acceptable threshold of people satisfied with the thermal environment.

The central atrium with roof fenestration, located in a library in Cyprus characterized by a coastal, windy climate with high air temperatures and relative humidity is an object of research in [88]. The atrium with skylights was supposed to provide natural lighting and improve the thermal comfort of the building, equipped with operable windows located around its perimeter. The authors emphasized the problem of summer overheating caused by the atrium skylights, which are impossible to eliminate by shading elements without loss of natural illumination, so the study investigated the implementation of a double-skin skylight to improve the thermal performance of the atrium without significant loss of natural lighting. The simulation method with EDSL TAS software was implemented, and the adaptive thermal comfort model was adopted to assess predicted occupants' thermal sensation. It was found, that implementation of a double-skin façade increases the air temperature in the upper part of the atrium, and enhances the effect of thermal buoyancy, stimulating natural ventilation during the summer season. Additionally, additional thermal insulation is provided for the winter season, as the original skylights were only 6 mm clear glass. Several operation strategies with different ratios of the opened windows and the double-skin façade materials were simulated for the winter and summer. According to the results, opening the atrium roof leads to an almost doubling of thermally comfortable working hours in the summer. Implementation of double-skin skylights improves thermal comfort during working hours even more significantly depending on the total area of fenestration opened, lowering the temperature in the building by enhancing natural ventilation. Importantly, no improvement in winter thermal performance was deducted. In addition to the original research, a wide literature review on the topic of atrium thermal performance and double-skin envelopes was presented in the paper.

The review paper [89] presents a systematic review of the literature on the daylighting performance of atria and fulfills the search criteria of this review but does not apply to issues related to ventilation and thermal comfort, so this paper is not reviewed.

A mechanically ventilated atrium of a Malaysian theme park is the subject of CFD (Ansys Fluent) simulation studies of heat and airflow in [90]. The authors conducted a simulation of natural ventilation driven by the buoyancy force and compared the resulting thermal comfort with those provided by fully-mechanical ventilation systems. According to their results, natural ventilation is ineffective and leads to worsening indoor thermal conditions in comparison to fully-mechanical ventilation, but hybrid ventilation with a fresh air inlet fan supplying exterior air to the lower part of an atrium to supplement the mechanical ventilation and cooling system can improve air distribution and maintain thermal comfort inside the atrium.

The articles are summarized in Table 7.

Table 7. List of other publications on ventilation and thermal comfort in atrium.

Authors	Year	Title	Journal DOI	Keywords
[77] J. Pang et al.	2023	Effects of complex spatial atrium geometric parameters on the energy performance of hotels in a cold climate zone in China	Journal of Building Engineering 10.1016/j.jobe.2023.106698	building energy performance; complex spatial atrium; design parameters; atrium platform position; slope of trapezoidal atrium profile
[78] C. Xu et al.	2023	Study on winter thermal environmental characteristics of the atrium space of teaching building in China's cold region	Journal of Building Engineering 10.1016/j.jobe.2023.105978	atrium space; cold region; measurement; teaching building; thermal environment
[79] H. Sahu, J. Vijayalaxmi	2023	Optimization of the Integrated Daylighting and Natural Ventilation in a Commercial Building	Lecture Notes in Civil Engineering 10.1007/978-981-19-9139-4_9	atrium optimization; daylighting; natural ventilation; thermal comfort; visual comfort
[80] J. Shaeri et al.	2023	Effects of sea-breeze natural ventilation on thermal comfort in low-rise buildings with diverse atrium roof shapes in BWh regions	Case Studies in Thermal Engineering 10.1016/j.csite.2022.102638	atrium roof shapes; sea-breeze; natural ventilation; thermal comfort; bushehr; BWh
[81] Y.H. Yau, U.A. Rajput	2023	Performance evaluation of an architecturally-designed vertical high capacity linear slot diffuser in a tropical atrium	Architectural Science Review 10.1080/00038628.2022.2140988	CFD simulation; tropical atrium; slot diffuser; turbulence model; deflector angle

Table 7. *Cont.*

Authors	Year	Title	Journal DOI	Keywords
[82] K. Ratajczak et al.	2022	Incorporating an atrium as a HVAC element for energy consumption reduction and thermal comfort improvement in a Polish climate	Energy and Buildings 10.1016/j.enbuild.2022.112592	atrium; daylighting; ventilation; building simulations; energy savings; university buildings; IES VE
[83] A. Ghazali et al.	2022	Indoor Thermal Comfort Perception at Atrium Zone: Case Study of Naturally Ventilated Public Market	Journal of Advanced Research in Applied Sciences and Engineering Technology 10.37934/araset.29.1.1329	thermal comfort; atrium zone; natural ventilation
[84] T. Corbett et al.	2020	Sensitivity analysis of proposed natural ventilation IEQ designs for archetypal open-plan office layouts in a temperate climate	Advances in Building Energy Research 10.1080/17512549.2020.1813197	buoyancy-driven ventilation; building design; computational fluid dynamics; internal environmental quality; natural ventilation; thermal comfort; water-bath modeling
[85] H.-H. Hsu et al.	2021	Hybrid Ventilation in an Air-Conditioned Office Building with a Multistory Atrium for Thermal Comfort: A Practical Case Study	Buildings 10.3390/buildings11120625	computational fluid dynamics (CFD); stack ventilation; displacement ventilation; atrium design; energy saving
[86] Y. Wen et al.	2020	Integrated design for underground space environment control of subway stations with atriums using piston ventilation	Indoor and Built Environment 10.1177/1420326X20941349	architectural design; atrium; piston effect; subway station; underground space; ventilation
[87] D.P. Albuquerque et al.	2020	Full-scale measurement and validated simulation of cooling-load reduction due to nighttime natural ventilation of a large atrium	Energy and Buildings 10.1016/j.enbuild.2020.110233	night cooling; natural ventilation; cooling load measurement; thermal comfort; EnergyPlus; CFD
[88] R. Sokkar, H.Z. Alibaba	2020	Thermal Comfort Improvement for Atrium Building with Double-Skin Skylight in the Mediterranean Climate	Sustainability 10.3390/su12062253	atrium; natural ventilation; thermal comfort; passive design strategy; Mediterranean climate; double skin skylight
[89] H. Omrany et al.	2020	Is atrium an ideal form for daylight in buildings?	Architectural Science Review 10.1080/00038628.2019.1683508	atrium; daylight; energy efficiency; visual comfort; sustainable design; atrium design
[90] N.A.M. Fohimi et al.	2020	CFD Simulation on Ventilation of an Indoor Atrium Space	CFD Letters 10.37934/cfdl.12.5.5259	CFD simulation; hybrid ventilation; atrium space

A review of recent research papers on ventilation and thermal comfort in atriums confirms the relevance of this topic and proves the need for further research. According to the presented studies, comprehensive analysis and optimization of architectural and engineering solutions allow the development of an atrium that improves not only the building's energy characteristic but also thermal comfort. As atriums are typically high spaces with many glazings, their interior thermal conditions are affected by many factors with great importance for solar heat gains and stack effects. Due to the high complexity of atrium thermal environments, a general conclusion can be drawn regarding the research methods used in the revised papers:

- The CFD analysis and in situ measurements are recognized as the most popular research methods to predict air movement (ventilation) patterns;
- Questionnaire surveys or calculations based on steady-state Fanger or adaptive thermal comfort models are used widely to assess thermal comfort.

8. The Future Directions of Research

This article reviews the latest publications on thermal comfort and ventilation in relation to various buildings present in public space. The results presented by the authors, the methods used, and the conclusions were analyzed.

The future directions of research, in analyzed articles relevant to buildings, include developing more advanced HVAC control systems which take into account online learning or predictive control. More buildings in different climate zones could be explored in the context of the transfer learning performance.

There are many more buildings and activities that also require special conditions, like sports buildings [91–95], including swimming pools [96–98] and fitness centers [99], as well as kindergartens [100–104], nurseries [105–107], museums [108–110], and churches [111–113].

The other group of papers on thermal comfort deals with methods of assessing thermal comfort [114–117] or on the subject of the personalization of comfort through ventilation [118,119]. Due to the assumed criteria for the selection of publications for the review and the extensiveness of the subject, the above issues have not been included. But the authors believe these are topics worth considering for future research.

9. Summary

A literature review of 53 articles on thermal comfort and ventilation for different types of buildings and spaces was conducted. In the articles, the conclusions, research methods, and limitations that could set directions for engineering activities that could bring benefits to society were sought. The most important findings are summarized below.

9.1. Office Buildings

Summarized findings of reviewed works in the field of thermal comfort and ventilation in office buildings are presented in Table 8.

In studies on offices, large, open spaces are most often studied [28,30–34]; sometimes the same offices in different locations are studied [31]. In the case of the research in [28], 52 spaces located in 26 cities from “ASHRAE RP-884 Database”, 57 cities located in 30 countries from “The Scales Project Dataset”, and 1 building (24 participants: 16 females, 8 males) from Medium US Office were numerically analyzed, and in [30] three different offices were analyzed. In terms of ventilation, there was both natural [31–33] and controlled [28–30,34] ventilation, with virtually no predominance of either system, which indicates the commonness of both types of ventilation in office buildings. In the analyses, measurements of air parameters in spaces [31,33] and measurements along with surveys on the feelings of their users [30,34] prevailed, but research works based on simulations [32], transfer learning [29], and a combination of simulations in EnergyPlus and machine learning algorithms [28] appeared. The discussed studies have many limitations given by their authors, among which one can specify the study of individual thermal comfort optimizing [28] or the study of only one office [29,30,32,33]. The authors also indicated that the results of the research should be supplemented with the results of questionnaires [31,32]. The main conclusions from the research are as follows.

Table 8. Summarized findings of reviewed works in the field of thermal comfort and ventilation in office buildings.

Paper	Space Type	Ventilation Type	Research Method	Number of Subjects	Limitations	Country, Climate	Main Findings
[28] Peng B., Hsieh S.-J.	Open-space office room	Controlled	Co-simulation (EnergyPlus and MATLAB))	1 open-space office room 4 citis (16 main batch	There is a high air exchange between cubes with individual valume flow rate of vent (formed in the middle of the room), so optimizing for the average of 6 cubes equals local discomfort (e.g., cool local climate for one objective).	Chicago, Phoenix, College Station, Tampa, United States of America	Novel hybrid data-driven thermal comfort model (PMV-SVM-ANN model) and HVAC control system which improve the thermal comfort of occupants in an open-space office room by 43.4–69.9% with slightly lower energy consumption (1–3.6%) were designed.
[29] Gao N et al.	Medium office	Controlled	Transfer learning with Algorithm TL-MLP-C * and TL-MLP	25,623 observations from ASHRAE RP-884 Database, 8225 participants from The Scales Project Dataset and 24 participants from Medium US Office Dataset (Philadelphia city, PA, USA).	Only the one office located in the 'temperate' climate zone was used as the target building. The best performance of prediction model is when at least six factors are provided and if there are lower (than six) then performance drops. Only MLP models were investigated.	Algorithm TL-MLP-C *:—Philadelphia, USA Algorithm TL-MLP: different climate zones all over the world	Developing of transfer-learning-based multilayer perceptron model in order to make thermal comfort prediction more precise (accuracy 54.5%)
[30] Yong, N.H. et al.	Open office	mechanical ventilation system	Measurments Surveys	3 office areas	Thermal environment and air quality were studied only at three office spaces.	Malaysia, tropics	Thermal comfort indices were indicated: the neutral temperature was 23.9 °C (that is 1.3 K lower than predicted 25.2 °C). About 81% of the occupants found their thermal environment comfortable with high rate of adaptation Phisical parameters, air quality, and ventilation rate per person were acceptable.
[31] M. Badeche, Bouchahm Y.	Office building with large glazing	Natural	Measurments According a Post Occupancy Evaluation (POE) method	4 office rooms located in diverse orientations (NE), (SE), (SW)	Thermal and visual comfort measurements only were conducted. For example, there is no information about occupant survey questionnaire, which is part of POE.	Algeria, Semi-arid climate	Impact of large glazing areas on thermal comfort and visual comfort. Natural ventilation was unable to release of accumulated heat gains. 86–100% of working-time was overheating, so adaptive solar façade, smart glazing, and moving shading devices was suggested.

Table 8. *Cont.*

Paper	Space Type	Ventilation Type	Research Method	Number of Subjects	Limitations	Country, Climate	Main Findings
[32] Ortiz, M.C., Morales, S., Cabrera, V.	Admission office at campus	Natural	CFD simulation (ANSYS Fluent 2019)	1 admission office	In order to improve the research and increase the number of satisfied users, it would be necessary to change the time step to hourly, conduct field surveys and introduce an adaptive approach.	Quito in Ecuador	Analysis of opening area of skylight, distributing louvers along the skylight, door position, impact of furniture in context of air movement in room, PMV, and PPD. Opening the door increases ventilation rates by 30%. Indoor air temperature equaled 18 °C and air speed in range: 0.25–0.75 m/s represented cool sensation (clothing level = 0.65) and slightly cool sensation (clothing level = 1.0). Indoor air temperature equaled 25 °C met thermal comfort.
[33] Lahji K., Puspitasari P.	Architecture studio room	Natural	Measurements:	1 architecture studio room	Only one room was analysed.	Jakarta in Indonesia	PMV value in range 2.23–3.27 (warm-hot thermal sensation) was observed and was correlated with wind velocity. In order to meet natural sensation, mechanical aids or hybrid air conditioning system is required.
[34] Borsos, Á. et al.	Open-plan office	Controlled	Measurments of IEQ Comfort survey	1 open-plan office, 216 respondents	1 There are no data on the IEQ parameters for air conditioning or no heating and no validation of the comfort map. Used A-weighted sound pressure level (LA) method underestimates the degree of noise produced by activities or sources characterized by a low-frequency contribution.	Budapest Hungary	65%, 50%, 47% of respondents were dissatisfied with the adjustability of noises and sounds, ventilation and thermal conditions, respectively, in the work environment. An office 'comfort map' based on occupants' individual IEQ preferences was developed.

In order to maintain a thermal comfort while minimizing office buildings' energy usage it is necessary to create an accurate thermal comfort model. Thermal comfort models based on thermal comfort data from room occupants achieve better performance than the PMV (predicted mean vote) model and adaptive model. On the other hand, it requires the collecting and processing of large data sets. Control of indoor air exchange in natural and mechanical ventilation systems is crucial to increase work productivity.

Thermal comfort in office buildings depends on the glazed area. In semi-arid climates, large glazing areas affect the high energy consumption of cooling systems to maintain comfortable temperature. Night ventilation absence is a reason for heat accumulation in the occupied zone.

In tropical climates, air extraction in buildings with natural ventilation (using skylight) is difficult because indoor and outdoor temperatures are similar. However, open doors increase ventilation rates (up to 30%).

Understanding office workers' individual preferences for IEQ affects increase of productivity. "Comfort maps" provide the opportunity to choose the optimal workplace.

Although it seems that office buildings are well researched, studies conducted in recent years indicate that there is further potential in their research, especially in terms of the thermal comfort of users. It should be borne in mind that research on thermal comfort in offices should use surveys and questionnaires, because feedback from people staying in offices may be important for recommending new models or guidelines for air parameter ranges. Simulations can be a response to performing research on a small research sample. Thanks to the measurement of the object and the execution of a digital twin, the data can be used for further simulations, thanks to which the number of tested cases will increase. The most common conclusion when inadequate thermal comfort of office users is detected is the recommendation to use air conditioning and/or controlled ventilation systems. According to the authors of this review paper, future research should also focus on the issues of improving controlling accuracy of the HVAC systems in offices in order to match the current needs of users while minimizing energy consumption for air treatment and its circulation.

9.2. Schools

Summarized findings of reviewed works in the field of thermal comfort and ventilation in schools are presented in Table 9.

The review included 18 articles. Most studies were conducted in primary schools [38–40,43,45–47]. In more than 80% of the analyzed cases, the subject of the analysis was natural ventilation, and in two (which are not review articles), air conditioning was included. The research methods used by the authors included in situ measurements [38,39,41–43,45,46,51], simulations [40,41,45–47], surveys: [42,43,51,52], and various combinations of those. Articles [36,44,53] are review articles.

The review of the literature on the impact of thermal comfort and ventilation on the ability to learn led to the following conclusions. Temperature is a very important factor affecting children's' performance. High temperatures cause a loss of concentration; students prefer cooler classroom temperatures than temperatures that adults feel as thermally neutral. In the tropical climate, cross-ventilation allows improving thermal comfort and maintaining the level of CO_2 concentration below 1000 ppm.

CO_2 concentration below 900 ppm avoids negative impact on learning ability. However, the exact correlation between CO_2 levels and learning ability should be further explored.

Table 9. Summarized findings of reviewed works in the field of thermal comfort and ventilation in school buildings.

Paper	Space Type	Ventilation Type	Research Method	Number of Subjects	Limitations	Country, Climate	Main Findings
[36] Manca S.; Cerina V.; Tobia V.; Sacchi S.; Fornara F. (2020)	School	Not specified	Systematic review;	68 empirical papers	Not specified	Various	A friendly environment (colors, ergonomic furniture. . .) as well as acoustic, thermal, and natural light comfort are important for the well-being and productivity of the users. The amount of ventilation affects student performance. Future research should emphasize individual variables of age, gender, specific needs, and interactions or coexistence of different variables to capture the high level of complexity of phenomena.
[40] Dudzińska A.; Kisilewicz T. (2021)	Primary school	Four variants: mechanical ventilation, forced night ventilation, natural night cooling, natural during the day and night	Simulation (Design Builder)	1 school 1 digital model	Results are valid for summertime	Budzów, Poland Summer	The role of mechanical ventilation and the possibility of night ventilation in reducing discomfort were investigated. Suggestion of the "aggregated measure of overheating" method for estimating hours of discomfort.
[41] Shrestha M.; Rijal H.B. (2023)	Secondary school	Natural	Field survey, simulation (DesignBuilder)	3 schools (one in Kathmandu, two in Dhading) Survey of 246 students, 737 responses (three-time votes)	Results are valid for summertime	Katmandu, Nepal Summer	Use of simulation in the design process to assess how the building behaves in terms of comfort and thermal environment. 1. Summer average comfort temperature: 26.9 °C. 2. Further studies should be conducted in different seasons and climates.
[42] Haddad S.; Synnefa A.; Ángel Padilla Marcos M.; Paolini R.; Delrue S.; Prasad D.; Santamouris M. (2021)	Secondary school	Mechanical ventilation (DCV)	Measurements, field survey	1 school, 2 adjacent classrooms The survey took place in late August to early September 2018 (305 responses) and in early April (377 responses)	Not specified	Sydney, Australia	Survey studies and Indoor Air Quality (IAQ) measurements confirm the influence of indoor temperature and CO_2 concentration on students' fatigue levels. It takes one week for students to adapt to a sudden change in the average outdoor temperature.

Table 9. *Cont.*

Paper	Space Type	Ventilation Type	Research Method	Number of Subjects	Limitations	Country, Climate	Main Findings
[44] Kapoor N.R.; Kumar A.; Alam T.; Kumar A.; Kulkarni K.S.; Blecich P. (2021)	School	Natural Controlled	Systematic Review Meta-Analyses (PRISMA);	37 articles	Not specified	India	A systematic review of Indoor Environmental Quality (IEQ) parameters related to research conducted in Indian school classrooms. The need for a standardized IEQ testing method in Indian schools.
[45] Lala B.; Kala S.M.; Rastogi A.; Dahiya K.; Yamaguchi H.; Hagishima A. (2022)	Primary school	Natural	Measurments, machine learning	5 schools, 14 classrooms, 512 students	Only one month-long field experiment	Dehradun, India	A comparative analysis of spatial variability in the performance of the machine learning model for children (in situ measurements) and adults (ASHRAE-II database).
[37] Peters T.; D'Penna K. (2020)	University	Natural	Semi-systematic review	32 articles	Not specified	Not specified	Openable windows should be used in study rooms. Enhancing ventilation improves cognitive performance. Each classroom and office should have windows on the exterior of the building, and if this is not possible, opening into the atrium to let daylight into the room. Natural ventilation reduces carbon dioxide levels, so air quality closer to serviced windows may be best to study.
[38] Suradhuhita P.P.; Setyowati E.; Prianto E. (2021)	Elementary school	Natural	Measurements	2 classrooms	Field measurements for the room temperature were carried out in the time range from 07:00–16:00 WIB on Wednesday, 2 June 2021	Indonesia (Jawa Tengah)	Openings in facades and the support of mechanical ventilation are necessary to ensure thermal comfort in accordance with the Indonesia National Standard.

Table 9. *Cont.*

Paper	Space Type	Ventilation Type	Research Method	Number of Subjects	Limitations	Country, Climate	Main Findings
[43] Mazlan A.N.; Saad S.; Yahya K.; Haron Z.; Abang Hasbollah D.Z.; Kasiman E.H.; Rahim N.A.; Salehudddin A.M. (2020)	School	Not specified	Measurement survey (Likert's scale rating)	2 schools in urban area, 2 schools in rural area	Measurments took place from 10 to 22 January 2019	Selangor, Malysia	On-field measurement and questionnaire survey revealed that urban areas experienced a rapid increase in temperature, while rural areas remained stable. The survey results confirmed that both students and teachers experienced reduced concentration when the indoor temperature was too high.
[46] Lan K.; Chen Y. (2022)	Primary school	Underground ventilation pipes and double-sided corridors	On-site monitoring in the classroom + numerical simulations based on finite element software	1 typical classroom and numerical model	Measurements five times a day from December to January	Shaanxi Province, China	Dual-sided corridors, underground ventilation ducts, and windows with a height/width ratio of 1 can provide energy-efficient and habitable building structures for primary school classrooms in the northern Shaanxi region of China.
[39] Talarosha B.; Satwiko P.; Aulia D.N. (2020)	Primary school	Natural cross -ventilation	Measurments	1 classroom	Measurment lasts only 4 days in April	Medan Helvetia, Indonesia	Despite the overheating in the classroom (indoor air temperature ranged from 30.5 °C to 34.5 °C), the median CO_2 concentration remained below 1000 ppm (maximum value: 637 ppm).
[47] Chang L.-Y.; Chang T.-B. (2023)	Elementary school	Natural ventilation, mechanical ventilation	Simulations (Python)	1 class of the school building; 4 variant A/C all day; delaying the turn-on time of the A/C system, turning the A/C system off during the lunch time period; turning the A/C system off during one class each afternoon.	Not specified	Taiwan	In connection with the plan to install air conditioning systems in all schools in Yuan, Taiwan, the authors conducted simulation studies on various air conditioning control strategies to achieve the average 8 h CO_2 concentration target in classrooms. The optimal strategy identified was operating the air conditioning throughout the school day in conjunction with a mechanical ventilation system providing a fresh air exchange rate of 5 l/s per person in the room.

Table 9. *Cont.*

Paper	Space Type	Ventilation Type	Research Method	Number of Subjects	Limitations	Country, Climate	Main Findings
[49] Tagliabue L.C.; Accardo D.; Kontoleon K.J.; Ciribini A.L.C. (2020)	Classroom	Natural	Simulation (EnergyPlus, Comsol Multiphysics)	Building energy model of the standard classroom; "Modulo Didactico" building model	Not specified	European climate zones (Italy, Greece, United Kingdom)	A dynamic simulation was conducted to assess the thermal performance of school buildings and explore possibilities for their improvement in several representative locations across Europe. It was demonstrated that thermal comfort in educational buildings during the summer can be achieved in certain temperate climate regions without the use of mechanical systems. In addition to this, informing users about building monitoring and management is crucial to ensuring thermal comfort conditions within the spaces.
[51] Fabozzi M.; Dama A. (2019)	University	Natural air-conditioning	Measurments Survey (ASHRAE 55 Standard)	16 classroom survey of 985 students	Evaluation took place in summer time	Milan, Italy Summer	The authors confirmed the utility of the Ranger model for predicting thermal sensations in air-conditioned classrooms with reasonable accuracy. In naturally ventilated classrooms, the adaptive model proved suitable for predicting students' comfort zones according to the ASHRAE 55 standard, while the adaptive comfort temperatures recommended by the EN 15,251 standard were unacceptable for a large number of students. There were no significant differences in the perception of thermal comfort between genders.

Table 9. *Cont.*

Paper	Space Type	Ventilation Type	Research Method	Number of Subjects	Limitations	Country, Climate	Main Findings
[52] López-Chao V.; Lorenzo A.A.; Saorín J.L.; De La Torre-Cantero J.; Melián-Díaz D.	Primary school	Natural	Survey based on the Indoor Physical Environment Perception scale (iPEP scale)	9 schools, 27 classrooms, 583 primary school students	There are no data on the IEQ parameters for air	Spain (Galicia)	The prognostic analysis of students' mathematics results confirmed their direct correlation with ventilation, room size, views, and attachment to place. It was also validated that the adaptation of the iPEP scale in the primary school is accurate and reliable.
[50] Grassie D.; Karakas F.; Schwartz Y.; Dong J.; Milner J.; Chalabi Z.; Mavrogianni A.; Mumovic D.	School	Natural	Simulations (EnergyPlus)	111 different combinations of naturally ventilated schools, from 5 different eras of construction, in 13 geographical regions	Modeling approach developed for naturally ventilated schools only	United Kingdom	A method called Data-driven Engine for Archetype Models of Schools (DREAMS) has been developed, based on the EnergyPlus stock modeling framework, which models different typologies of classrooms and takes into account not only indoor environmental quality criteria but also academic achievements, health, and healthcare costs.
[53] Sadrizadeh S.; Yao R.; Yuan F.; Awbi H.; Bahnfleth W.; Bi Y.; Cao G.; Croitoru C.; de Dear R.; Haghighat F.; Kumar P.; Malayeri M.; Nasiri F.; Ruud M.; Sadeghian P.; Wargocki P.; Xiong J.; Yu W.; Li B. (2022)	School	Different types	Critical review	304 publications	Not specified	Various	A comprehensive review of research from the last 50 years concerning indoor air quality in classrooms across more than 40 countries.
[48] Catalina T.; Damian A.; Vartires A.; Nița M.; Racovițeanu V. (2023)	Secondary school	Natural	Measurments	2 clasrooms	Not specified	Romania	Ventilation in classrooms is mandatory to achieve a satisfactory level of thermal comfort and indoor air quality, and even natural ventilation through window opening remains a simple and effective tool to reduce pollutant concentrations in indoor spaces.

It is not possible to give a one-size-fits-all comfort temperature range for all educational buildings because it depends on many factors, including the climate zone and students' previous exposure to air conditioning. But night ventilation allows reducing thermal discomfort during the day.

The publications often lack information about the limitations of research, but they can mainly be defined as conducting research only for one period of the year [40,41,51] or covering only a short measurement period [38,39,45,46].

Educational buildings are designed for different age groups: children, teenagers, adults, as well as for various types of activities—science, artistic expression, sports, but also office work. In studies conducted in schools, it is good to use a holistic approach, because a lot of elements affect the effectiveness of the learning process [36,37,52]. The planned research may take into account the different purpose of the rooms and the different ages of the participants, which may affect the responses to the survey. It is worth noting that in the cited studies, schools are mainly equipped with natural ventilation, which means that thermal comfort is often not achieved, not to mention the quality of indoor air, which is often poor in educational buildings. This indicates a new direction of research on ventilation systems that could be used in existing buildings for such a purpose. When designing new educational buildings or during the renovation process, computer simulations can be an important tool. However, for the simulations to reflect reality, it is very important to introduce parameters that precisely define the characteristics of the building along with its technical equipment, surroundings, and users, which is why expanding/defining simulation algorithms and machine learning so that they take into account the specificity of individual age groups (children, youth, adults) seems to be important.

9.3. Hospitals

Summarized findings of reviewed works in the field of thermal comfort and ventilation in hospitals are presented in Table 10.

Research on hospitals is conducted for various spaces in hospitals: hospital ward [57,61], emergency room [59], operation room [59,60,62,64], intensive care unit [59], or nursing home [63]. It would be expected that healthcare facilities should have controlled ventilation through which a better indoor environment can be achieved, and this is indeed the case. Natural ventilation/controlled ventilation/both types of ventilation were present in correspondingly 29%/57%/14% of the reviewed papers. Most studies use controlled ventilation [59–62,64]. There are various research methods: simulations [57,60,62,64], in situ measurements [57,59,61,62], surveys [57,61–63], and their various combinations. The main limitations are the inability to generalize the results due to the test conditions in only one climate [59,61,63] or the limited number of analyzed systems [60,64]. The main the main insights after the literature review are summarized below.

A review of research papers and review articles on ventilation and thermal comfort in hospitals shows that this is a subject that still requires continuous research. The multitude of parameters affecting the final effect does not allow for simple and universal conclusions and recommendations. Climate, tightness of the building envelope, ventilation system, control of its operation, staff attire, type of room (operating room, hospital ward, others), and type of patient illness are just some of them. To this day, it is not settled which ventilation system should be used and when to ensure adequate air quality and thermal comfort. New technologies are being developed to ensure thermal comfort for both patients and hospital staff (divergence of interests), aiming at ad hoc (temporary) warming of the patient during surgery in order to avoid hypothermia, also with the use of intravenous warming substances.

Table 10. Summarized findings of reviewed works in the field of thermal comfort and ventilation in hospitals.

Paper	Space Type	Ventilation Type	Research Method	Number of Subjects	Limitations	Country, Climate	Main Findings (General)
[57] Abd Rahman, Noor Muhammad et al.	Hospital wards	Natural	Simulation, in situ measurement, surveys	1 hospital ward located on the 3rd floor (last floor)	Results are not presented for the similar rooms from the 1st and 2nd floors, which are air-conditioned. A comparison in terms of thermal comfort and energy consumption would be interesting.	Malaysia	More than half of the total occupants in the ward feel discomfort, with a predicted mean vote (PMV) between 1.0 and 1.6 and a predicted percentage of dissatisfied between 40% and 56%. "People in a tropical climate zone are well accustomed to hot-humid weather and would tolerate high temperatures."
[59] Khan M. et al.	Emergency room, operation room, intensive care unit medical ward	Natural and controlled	in situ measurements	4 hospitals and 4 space types in each	The results and conclusions are accurate for the hot climate.	Pakistan	Temperature, relative humidity, and carbon dioxide were measured. "The results show that occupancy rate, ambient thermal conditions, type of HVAC system, and building orientation are vital drivers of IEQ".
[60] Tsung-Yi Chien et al.	Operating room	Controlled	Simulation	3 variants of HVAC system: (i) "conventional"; (ii) "liquid desiccant air conditioning system (LDAC)"; (iii) rotary desiccant air conditioning system (RDAC)	Three systems were analyzed and the best one was selected. There are more possibilities and they are related to the type of operation and its specific requirements. The conclusions may therefore not be appropriate for every situation.	Taiwan	RDAC (rotary desiccant air-conditioning system) is preferable as the most energy-efficient for the operating room.

Table 10. *Cont.*

Paper	Space Type	Ventilation Type	Research Method	Number of Subjects	Limitations	Country, Climate	Main Findings (General)
[61] Nishesh Jain et al.	Hospital wards	Controlled	In situ measurement site visits semi-structured interviews with the facility managers	3 hospital wards located at 3rd, 4th, and 7th floor; 47 responses on the survey	Measurements and surveys were carried out in the new building to draw conclusions for buildings designed in the future. Three rooms in a single building in the UK climate were analyzed. The conclusions are not universal for other room types, other HVAC systems, or other climate zones.	United Kingdom	Temperature, RH, CO_2, PM2.5, PM10, NO_2, VOCs, electricity and gas use were measured. "The study highlights the need for an integrated and holistic approach to building performance to ensure that healthy environments are provided while energy efficiency targets are met."
[62] Fan, Minchao et al.	Operating room	Controlled	Simulation, in situ measurement, surveys	2 types of ventilation system: laminar or mixing for two real-size operating rooms	The presented method seems to be universal for a comprehensive assessment of the quality of the HVAC system and the energy consumption of operating rooms. It has been validated in only two operating theatres: laminar and mixing ventilation systems.	Norway	The method to assess ventilation systems in hospitals based on the "analytic hierarchy process and fuzzy comprehensive evaluation" is presented. Taking into account 7 parameters in the context of 3 evaluation criteria: "Ventilation effectiveness, energy consumption, and users' satisfaction". Multi-criteria decision making. Problem was solved. Laminar system was assessed as satisfying and mixed as dissatisfying.

Table 10. *Cont.*

Paper	Space Type	Ventilation Type	Research Method	Number of Subjects	Limitations	Country, Climate	Main Findings (General)
[63] N. Forcada et al.	Nursing home	Natural	Surveys	5 nursing homes	The results and conclusions are accurate for Mediterranean climate.	Spain	The use of natural ventilation without air conditioning can reduce energy consumption without significantly affecting the thermal comfort of residents. ASHRAE 55:2020 thermal comfort model can be considered as close to the expectations of nursing home residents.
[64] Gutierrez, Albio D. et al.	Operating room	Controlled	Simulation	Single operating room	Simulations were carried out for one variant of the operating room with one of the many possible HVAC systems.	Colombia, USA	CFD simulations to calculate predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) in the operating room. The temperature and airflow patterns were investigated to show that proper design is needed to obtain comfortable conditions.

Ventilation in hospital buildings plays an important role in ensuring sanitary safety, removing pollutants and maintaining thermal comfort. However, the choice of the ventilation system remains controversial—although laminar systems seem to be the most advantageous, there is no one universal solution that will work in every case nor guidelines that would show when to use which type of system. In addition, most works emphasize that ventilation systems in hospitals, in particular in operating rooms, are energy-intensive and should be energy optimized.

Research in hospitals is difficult to conduct because the hospital consists of many different spaces with different purposes and requirements. There are patients with different health conditions, so it can be difficult to survey them. The conditions of care are not conducive to carrying out measurements. It seems that simulations can be a good way to find new, profitable solutions. Validation measurements should be used as well as those that allow the creation of a digital model for simulation purposes. Simulations allow us to take into account more various cases and make the possibility of comparing results for different locations. A limitation in generalizing conclusions may also be the different local regulations in force in each country.

9.4. Bedrooms

Summarized findings of reviewed works in the field of thermal comfort and ventilation while sleeping are presented in Table 11.

The presented articles concerned several aspects related to ventilation and thermal comfort in bedrooms. Although the authors presented valuable results, it can be noted that the described studies contain small samples of the studied objects. The largest research sample involved surveying 517 people in Denmark [68]. Thanks to this, the authors obtained a picture of the ventilation systems used in this country. A greater number of analyzed variants is also found when simulations are used for research, mainly CFD [66,72,73]. Thanks to this, the authors analyzed from 3 to 24 different situations. In 100% of such works, the CFD models were validated against experimental data carried out in a climatic chamber or using a laboratory stand. Ansys Fluent or Solidworks software were used for simulations, whereas in cases where experiments were conducted, the authors performed field tests in one building up to a maximum of three rooms within one study [65,69–71,74]. Cases in which the measurements took place in a climatic chamber prevail [67].

Research on thermal comfort in bedrooms and while sleeping is carried out all over the world, and their results usually refer to specific climatic conditions. The ones discussed concerned the summer period [65,67] and heating seasons [68–73] or did not specify the period of the year due to the nature of the analyses conducted (influence of air movement). Both types of ventilation were present in correspondingly reviewed papers, but part of the research took place in a laboratory.

Good indoor air quality and proper thermal conditions are a key factors that may provide good sleep quality. To achieve it, there are some recommendations that may be followed. In the case of buildings located in countries with warm climates, the lack of air movement in the room may cause a problem with sleep. The guideline addressed to designers and implementers of building modernization resulting from the conducted research is the recommendation for air movement. When designing systems to ensure proper sleeping conditions, it is more important to pay attention to ventilation and air movement than to the temperature of the supplied air. This may be achieved by introducing local devices in bedrooms. Thanks to this, the air conditioning will only be able to work in the event of a very high air temperature.

Table 11. Summarized findings of reviewed works in the field of thermal comfort and ventilation while sleeping.

Paper	Space Type	Ventilation Type	Research Method	Number of Subjects	Limitations	Country, Climate	Main Findings
[65] Jakob B. Knudsen et al.	Bedroom in traditional Gambian building	Natural	Measurements	2 experiments (1) Measurements of five methods for assessing ventilation in two houses; (2) Measurements of CO_2 concentration in 5 similar houses.	External parameters between the night vary (weather, wind). Future CFD modeling study designed to improve airflow. in buildings to keep the occupants comfortable while keeping out mosquitoes.	Gambia (Africa) Climate: hot and humid Summer season	Recommendations of providing air movements in bedrooms and air exchange. Recommendation for airtightness tests for old-type buildings. Recommendation of the different construction of houses—adding screened doors and windows to the house. The conclusion that proper ventilation may protect against malaria.
[66] Haiguo Yin et al.	Climatic chamber Tiny sleeping spaces in full scale	Controlled	CFD simulations Validation measurements	Three scenarios of data: (1) Airflow change; (2) Supply air temperature change; (3) Air distribution change.	Not specified	China	Recommendation of providing ventilation with air movements (0.24 m/s) to keep thermal comfort during falling asleep.
[67] Chenqiu Du et. Al.	Climatic chamber Representation of bedroom	Controlled	Measurements (experiments)	24 people 3 sets of air parameters (temperature, relative humidity, and air velocity) Total Sleep Time (TST), Sleep Onset Latency (SOL), and Slow-Wave Sleep (SWS)	The values used for the bedding system are not able to reflect accurately the actual thermal resistance when sleeping. Conclusions are based only on one limited experiment and need more experimental studies and tests to describe typical scenarios. The use of wired temperature sensors in this study may cause discomfort for subjects during sleep. Other factors like air quality, CO_2 concentration, lighting, noise, etc., were not included but may have an impact.	China Summer season	A PMV model was proposed considering three aspects of the body heat exchanges: the parts in contact with the mattress (e.g., back, buttocks), the parts covered by the quilts or clothes (e.g., abdomen, chest), and the parts directly exposed to the air (e.g., head, arms, legs) Recommendation of providing air movement at air temperature 28–32 °C. Guidelines for adopting air movements to improve thermal environments whilst saving energy by the installation of local fans will be beneficial for thermal comfort and energy.

Table 11. *Cont.*

Paper	Space Type	Ventilation Type	Research Method	Number of Subjects	Limitations	Country, Climate	Main Findings
[68] Chenxi Liao et al.	Existing bedrooms in Denmark	35.3%% mechanical ventilation 24.6% exhaust ventilation 49.9% natural ventilation	Survey (1) Type of ventilation, bedroom, surroundings, and location (2) Subjective sleep quality—Pittsburgh Sleep Quality Index (PSQI)	517 people	Results are for the heating season, and to generalize them, more data from non-heating seasons are needed. Results are based on a survey, so field measurements are necessary to validate them.	Denmark Winter—heating season	People respond with their behavior to thermal conditions in the bedroom, e.g., by opening the window when the air feels stuffy. In most residential buildings in Denmark, there is natural ventilation. In bedrooms with mechanical ventilation, people feel more comfortable conditions. Recommendation of a combination of objective and subjective research will allow future solutions to be proposed—e.g., opening windows before sleeping.
[69] Dan Mio et al.	Student dormitories	Natural	Survey Maesurments: IEQ parameters	Two 4-bed bedrooms	Results are limited to similar room types and climates. The sample of respondents was small. The research should be repeated in a larger sample of similar objects and models should be created. Recommendations of providing more field studies with measurements and surveys should be done in the future to help implement guidelines.	Beijing, China Heating season	Analyzed dormitories were of poor air quality. Correlation between subjective and objective results exists. Recommendation of providing local air movement devices, using earplugs.
[70] D.A. Adincu et al.	Bedrooms in a refurbished building	Natural	Measurements (temperature, relative humidity, CO_2)	3 bedrooms with different numbers of people.	Results are limited to the pollution concentration inside specific rooms. The authors plan for extended further experiments.	Bucharest, Romania Winter season	Analyzed bedrooms were of poor air quality because of a lack of mechanical ventilation. Airing is not effective for providing proper indoor air quality and during winter it may lower room temperature. Use of sensor-controlled mechanical ventilation. Use of sensor-controlled mechanical ventilation.

Table 11. *Cont.*

Paper	Space Type	Ventilation Type	Research Method	Number of Subjects	Limitations	Country, Climate	Main Findings
[71] Mohammad Al-Rawi	Residential house Children's bedroom	Natural	Measurements CFD simulations (SOLIDWORKS)	1 bedroom A short period of time	The authors stated that further research should be performed on the impact of humidity of outside air the on performance of a heat pump.	Waikato, New Zeland Winter season	Air temperature during sleep is low in New Zealand houses because of poor insulation, insufficient ventilation, and lack of financial resources for heating bills. The use of heat pumps for heating by which a PMV index of 0.72 may be reached is proposed.
[72] Jian Liu and Zhang Lin	Climatic chamber Laboratory stand	Controlled	Simulations CFD (Fluent)	17 cases	Not specified	China Winter season	A new type of heating system—stratum ventilation heating—allows for blowing air from the side of the head, which provides an appropriate distribution system for proper thermal comfort in the bedroom.
[73] Jian Liu and Zhang Lin	Climatic chamber Laboratory stand	Controlled	Simulations CFD (Fluent)	3 air-distribution systems 7 supply air temperatures 3 levels of PMV	Not specified	China Winter season	By supplying air to the occupied zone, with the same value of PMV, 10% energy savings may be achieved in comparison of other air distribution and heating systems.
[74] Chandra Sekhar et al.	Semi-detached house (SDH) Apartment (A)	Natural (SDH) Controlled (A)	Measurements (t, RH, CO_2) Simulations	2 bedrooms 9 variants of different use of a bedroom	Not specified	Denmark Heating season	To ensure air quality at the right level (CO_2 concentration of 1000 ppm), the use of the bedroom should be adapted to the type of ventilation. In bedrooms with natural ventilation, door should be opened during sleep. For mechanical ventilation, air exchange of 0.6 h^{-1} allows for maintaining CO_2 concentration below 1000 ppm.

Still, there is a need to conduct field studies on the quality of sleep and the quality of the indoor environment in order to be able to better recommend various beneficial design solutions for people to improve their well-being at home. Each measurement should be supplemented with surveys, which may be helpful in future works. Surveys may give reliable results that can be obtained without the need to mount sensors. But additional, even local measurements, can show the effectiveness of certain actions.

The authors most often give limitations that apply to the conducted research. Among them, the most common limitation, which can also be attributed to cases where the authors themselves did not take it into account, is usually a small research sample [65,69–71]. An additional limitation is conducting the research in a selected season of the year [68–70,74], which is important, especially when there is natural ventilation in the analyzed building [65,69–71,74]. A certain limitation is also the use of only simulations and conducting research on experimental stands, which may not reflect the real conditions of the bedroom.

In order to overcome the defined limitations of the cited studies, when planning research work on the subject of sleep quality and air parameters in bedrooms, one should follow the authors of already published studies. Research should be planned covering the period of the heating season as well as the time outside the heating season. The research sample should be expanded, although this may be difficult due to the nature of the research. Survey research (subjective) should be supplemented with objective research (measurement).

Regardless of the planned research, even in the case of a small research sample, field studies on sleep parameters and air parameters in bedrooms are important and should be continued due to the fact that good sleep quality is extremely important for well-being and health, and people spend one-third of their lives sleeping.

9.5. Atria

Summarized findings of reviewed works in the field of thermal comfort and ventilation in buildings with atriums are presented in Table 12.

The atrium is a building element that occurs all over the world. The analyzed studies concerned various types of buildings: offices [84,85], educational [78,82,88], commercial [77,79,83,87], and others [80,81,90]. In most of the analyses, the authors use computational simulations [77,79–82,84,85,87,88,90] to simulate the thermal state of the zone and calculate thermal comfort identifiers. Mostly, the CFD tools were used. Only in the case of two studies, the authors performed in situ measurements and used questionnaires [78,83] to draw some scientific conclusions directly, although in some papers the in situ measurements were used as additional research tools to validate the accuracy of the developed computational models [79,87]. The central atrium is the most studied type, and mainly only one selected atrium case was analyzed [77–82,85,87,88,90], except for [83], in which two atrial spaces were researched. However, the use of simulation software allowed one to analyze multiple cases of the same atrium differing in particular physical and operational parameters.

In terms of the type of ventilation occurring in the analyzed atrial buildings, natural ventilation is the most common [79,80,83–85,87,88,90] as the atrium may increase its efficiency (natural ventilation was presented in about 67% of reviewed papers). The controlled ventilation is less popular in the reviewed papers, but the interaction of the atrium with this type of HVAC system was also studied in [78,81,82,90] (which is about 33% of the reviewed papers).

Table 12. Summarized findings of reviewed works in the field of thermal comfort and ventilation in buildings with atrium.

Paper	Space Type	Ventilation Type	Research Method	Number of Subjects	Limitations	Country, Climate	Main Findings
[77] J. Pang et al.	Hotel	Not specified	Simulations (Ansys Fluent, Design Builder),	Single central atrium, 27 simulation cases with different atrium shape and size	The findings may be useful only for atriums with platform at the lower levels, as it greatly affects thermal conditions.	China	Height, platform location, and the opaque-to-transparent surface ratio of the atrium are factors of high importance for atrium energy performance.
[78] C. Xu et al.	College	Controlled	In situ measurement, surveys	Single central atrium, 70 questionnaires	The findings are based on a single, specific case study (winter, central atrium, specific ventilation system, radiant heating).	China, Winter	Fanger model overestimates thermal comfort for an atrium with central skylights. An original formula for PMV for that kind of space is provided.
[79] H. Sahu, J. Vijayalaxmi	Commercial	Natural	Simulations	Single central atrium, 11 design variables simulated	The findings are based on the computational model designed and validated for the selected single-type of central atrium.	India	The window-to-wall ratio and the glazing type are selected as important parameters affecting the thermal comfort in the central atrium with natural ventilation. The ventilation strategy, including window opening area and schedule, allow a decrease in the energy consumption for cooling.
[80] J. Shaeri et al.	Not mentioned	Natural	CFD simulations (Ansys Fluent)	Central atrium in low-rise building, 12 roof shapes	Simulations take into account the sea breeze impact on the atrium. Natural ventilation efficiency, which is valid for coastal cases.	Iran	The roof shape impacts the natural ventilation of the atrium and thermal comfort.
[81] Y.H. Yau, U.A. Rajput	Anonymous skyscraper	Controlled	CFD simulations	Single hexagonal atrium	The study investigates specific air distribution system with linear diffusers and low-level cool air supply.	Malaysia	A specific solution of ventilation air supply through diffusers with high air supply velocities (>6.5 m/s) and exhaust air from under the supply diffusers ensures good thermal comfort in the ring-shaped atrium.

Table 12. *Cont.*

Paper	Space Type	Ventilation Type	Research Method	Number of Subjects	Limitations	Country, Climate	Main Findings
[82] K. Ratajczak et al.	University	Controlled	Simulations (IES-VE)	Single central atrium	The study focuses on the energy efficiency and does not quantitatively analyze thermal comfort in detail.	Poland	Incorporating a central atrium with a glazed roof provides natural light to the adjacent spaces, lowering the internal heat gain and impacting the HVAC system's performance. An atrium can be used as a passive heater for fresh air in a moderate climate.
[83] A. Ghazali et al.	Public market	Natural	In situ measurements, surveys	2 central atriums, measurements conducted for 7 days in May, traders surveyed	As the surveys are addressed to traders, conducted thermal comfort analysis is valid for the long exposure and relatively permanent location of the subjects. The results for visitors would likely be different.	Malaysia	Thermal comfort is not provided with central ceiling fans, and the local fans are used to neutralize the effect of high temperature and humidity.
[84] T. Corbett et al.	Open-plan office	Natural	CFD simulations (ANSYS-CFX), water bath modeling	9 cases, with 3 types of the central atrium and 3 types of the building core	Simulations performed with simplified, constant climatic conditions not corresponding to winter and summer.	United Kingdom	The natural ventilation efficiency in the building with a central atrium is very sensitive to the design of the perimeter openings.
[85] H.-H. Hsu et al.	Office	Natural, hybrid	CFD simulations	Case study of single central atrium	The results are obtained for the specific tall building with two atriums central atriums opened to the perimeter air-conditioned spaces: first in the lower part, with the wall-opening, and the second one in the upper part, with the roof-opening	Taiwan	Stack ventilation is unsuitable when the external temperature is higher than the internal temperature, which is typical for air-conditioned buildings. The hybrid ventilation scheme is developed for the atrium surrounded by air-conditioned spaces, in which the air is transferred to the atrium from neighboring spaces.

Table 12. *Cont.*

Paper	Space Type	Ventilation Type	Research Method	Number of Subjects	Limitations	Country, Climate	Main Findings
[87] D.P. Albuquerque et al.	Non-residential	Natural	Simulations (EnergyPlus), CFD (Ansys Fluent), in situ measurements	Single central atrium, analyzed on several summer days	The study covers interaction between passive cooling and radiant cooling floor, which is a specific cooling system impacting significantly the air flow pattern in the zone.	Portugal	The passive cooling provided by nighttime ventilation allows reduction of the cooling load for active cooling systems in atrial spaces by about 27%. Relatively small openings can be used for passive cooling.
[88] R. Sokkar, H.Z. Alibaba	Library	Natural	Simulations (EDSL Tas)	Single central atrium, several dozen cases	Authors noted that their results are influenced by large transparent facades, but they found it an average model.	Cyprus	The central atrium with skylights provides good natural lighting; however, it also causes summer overheating that is impossible to be eliminated by shading without loss of natural lighting. Double-skin facade for the skylights connected with the operable skylights is the solution for enhancing natural ventilation and improving thermal comfort during the summer season.
[90] N.A.M. Fohimi et al.	Indoor theme park	Natural, controlled	CFD simulations	Single atrium	The study investigates single, specific case. Although some conclusions are drawn, they cannot be generalized.	Malaysia	Mechanically-driven ventilation provides better thermal comfort than the natural, buoyancy driven ventilation in the air-conditioned space.

The main conclusions from the study of buildings with atriums are as follows.

An atrium designed taking into account the naturally occurring stack forces can significantly improve the conditions of thermal comfort related to the air temperature, humidity, and velocity, but it requires an analysis of many geometric parameters, not only of the atrium itself but also of the whole building, as well as a ventilation system and local climatic conditions, as various synergistic effects can significantly affect ventilation efficiency and thermal comfort.

A properly selected ventilation strategy and configuration of the ventilation system together with the architectural parameters of the atrium allow for a significant improvement in thermal comfort indicators in the atrium and adjacent spaces and can lead to a reduction in the energy demand of the building's HVAC systems, which is proved by many reviewed case studies.

In general, atrial spaces allow taking advantage of the stack effect and implementation of natural, non-mechanically-driven ventilation, which is the most commonly seen potential for improving energy efficiency and thermal comfort, being verified in many research papers. According to the complexity of the atrium's thermal environment, the CFD simulation tools are widely used, with satisfactory accuracy confirmed by many in situ measurements.

The main limitations in research on atrium buildings are mainly related to the number of research facilities, as mentioned above. The limitations are related to the analysis of the selected special architecture of the facility [77,85,88] and specific boundary conditions, e.g., climate [78–81,83,84,87,90]. As the atrial spaces can be, according to reviewed papers, very sensitive to small changes in individual design parameters (both physical and operational parameters of the atrium itself) as well as the properties of the external environment (i.e., temperature, solar radiation, wind), there are plenty of possible boundary conditions. This makes it difficult to relate the results obtained for a particular atrium to another, not identical one.

To overcome the defined limitations of the cited studies, when planning future research work on the subject of atrial buildings, it seems appropriate to study other types of specific atrial buildings, taking into account their individual physical and operational parameters to further understand the thermal characteristics and thermal comfort of the atrium and expand the research case database. Research taking into account not only one particular set of boundary conditions (including exterior climate parameters, at least in the winter/summer season) may contribute greatly to the field and allow drawing more universal conclusions.

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