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Review

A review on significance of thermal comfort in educational facilities

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Abstract: Climate change and the urgency of decarbonizing the built environment drive technological innovation in delivering thermal comfort to occupants. Studies have shown that thermal discomfort can lead to a decline in students' cognitive function, motivation, absenteeism, and a decrease in instructors' work performance. This article reviews significant changes, developments, and trends in thermal comfort research for educational facilities classrooms. This study summarizes research regarding the importance of environmental comfort in education facilities, different climatic regions, and various parameters that play a vital role in determining thermal comfort. The investigation of the current literature showed that researchers focused on different issues, adopting diverse models and indices to investigate thermal comfort in classrooms. Indeed, even if the environmental conditions comply with standards, in several cases, a prolonged stay indoors affects the health and productivity of students. However, it is important to focus on students' preferences in different regions, climates, and educational stages to create healthy and human-centered buildings. It is also clear that current research trends mainly focus on cold regions of Europe, while, by educational level, secondary-stage classrooms are the least investigated; thus, further investigation is needed. Therefore, an integrated approach that considers both the positive and negative effects of indoor exposure is needed, including the individual preferences and needs of occupants in the least researched regions, such as Asia and Africa.

Keywords: climate change; productivity; health; educational facilities; building occupants; student's performance

1. Introduction

The world is experiencing an energy crisis because of rising energy consumption and the slow depletion of fossil fuels. Building energy usage accounts for 40% of overall energy use, primarily due to maintaining a suitable thermal environment [1]. For this reason, researching thermal comfort is essential to reducing energy use and fostering a comfortable indoor atmosphere. Building thermal discomfort has been identified as a significant contributing cause to several health-related problems, from decreased productivity to severe illnesses and even death. People are vulnerable to the adverse effects of the interior thermal environment, which can result in various health issues [2].

Thermal comfort is a state of mind indicating contentment with the thermal surroundings. When 80% of building occupants are satisfied with the indoor environment, thermal comfort is attained according to ASHRAE-55 standard [3]. When formulating a broad thermal comfort theory, researchers fundamentally disagree due to the complexity and personal preferences of the users [4]. Nonetheless, a few experts concur that people's perceptions of temperature are influenced by additional personal factors, clothing, activity, and four environmental factors such as temperature, thermal radiation, humidity, and air speed.

Thermal comfort in educational buildings, especially classrooms, is essential for several reasons, including student performance, health and well-being, attendance, teacher satisfaction, and learning environment [5]. The function of educational facilities in generating a constructive educational environment and promoting environmental consciousness has been increasingly recognized in recent years [6], [7–9]. Cold or heat stress can create thermal pain and diminish motivation to exert effort during work [10]. According to several research findings, many classrooms do not operate as planned throughout the design phase in terms of their indoor environment conditions. According to Giulia Lamberti [11], students spend so much time in classrooms, and the thermal environment in educational buildings is critical to their health and productivity. Singh [12] conducted a study to determine the progress in classroom-based thermal comfort studies and found that primary school students were the least sensitive to changes in outdoor temperature. This is further explored in the analysis section.

As reflected in **Figure 1**, thermal comfort has been thoroughly studied since 2021, and around 50,000 research articles have been published in this domain. Thermal comfort has remained a subject of interest for the last century. **Figure 2** presents the increase in the trend of thermal comfort research in the last twenty-three years due to global challenges of an energy crisis, climate change, and financial constraints. Considering the global interest in sustainability, most publications focus on buildings' performance concerning energy and the environment. Researchers are investigating innovative strategies to ensure thermal comfort in several buildings through passive and active means. The term thermal comfort was searched, and according to building type, as shown in **Figure 3**, it is most widely researched for residential buildings. This infers that educational facilities and other building types, such as healthcare facilities, need the attention of researchers to investigate their thermal comfort conditions.

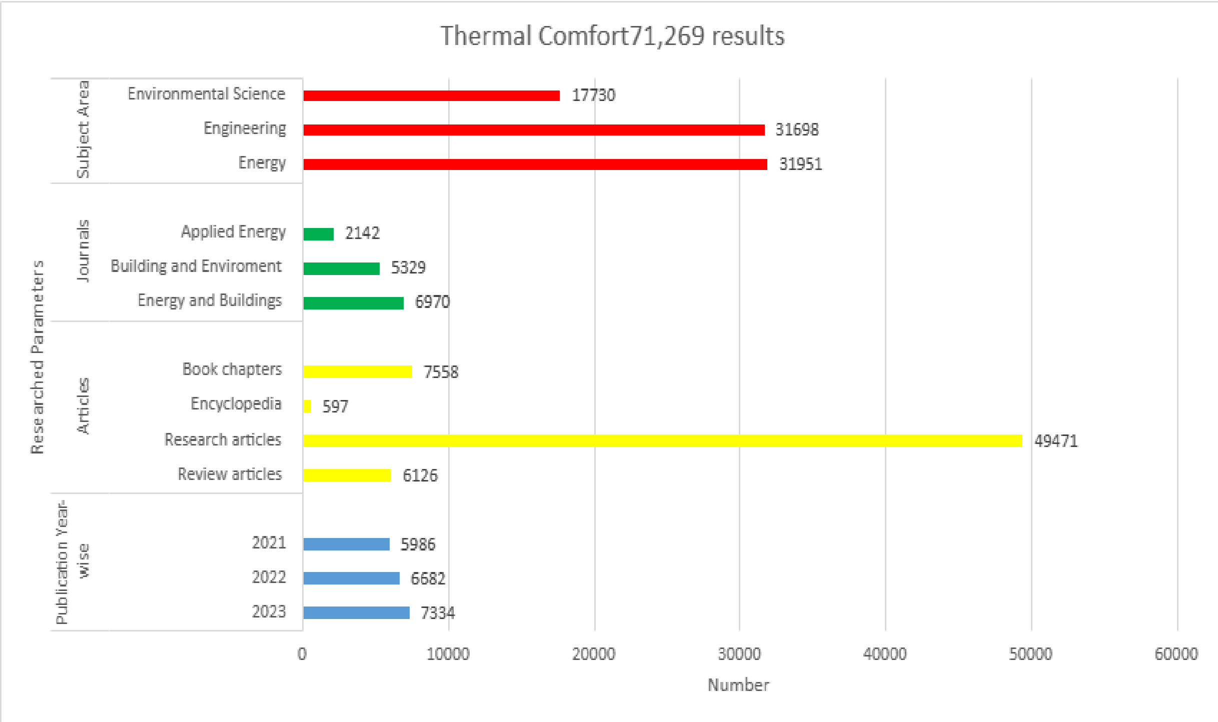

Figure 1. Thermal comfort studies (2021–2023).

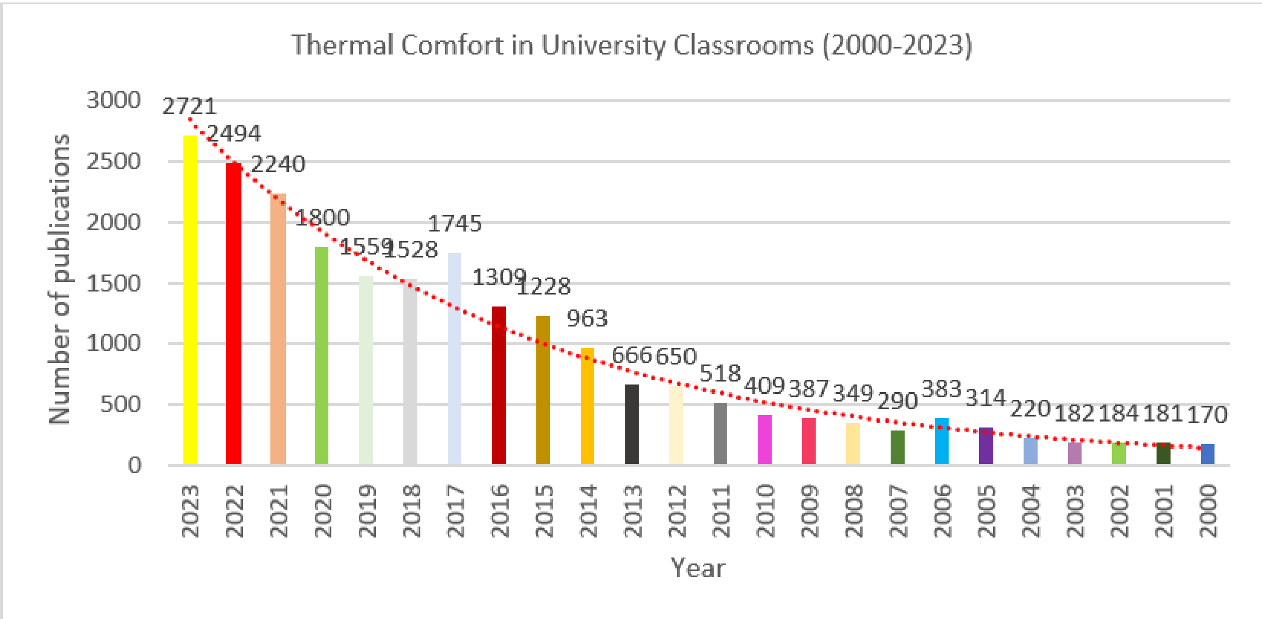

Figure 2. Thermal comfort year-wise published articles.

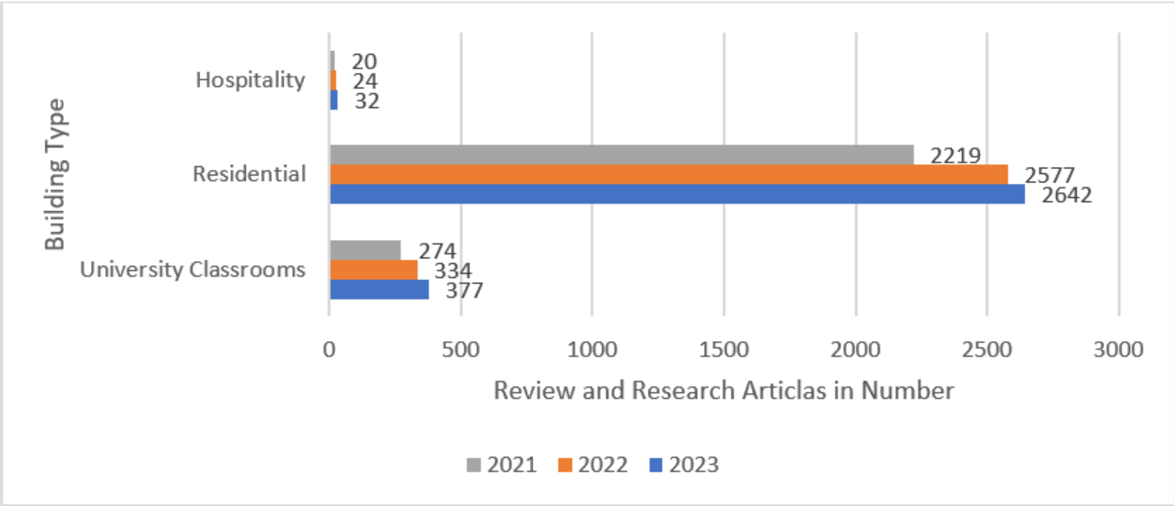

Figure 3. Thermal Comfort research by building type.

By focusing on secondary schools, which are underrepresented in regions like Asia and Africa, and a topic that is not well-studied in thermal comfort studies, this work fills a critical research vacuum. This kind of focus ensures inclusivity and advances global environmental goals. The current study will look into research trends in educational facilities based on educational levels and geographical climates. The most important evaluation criteria from earlier research will also be evaluated to have a better understanding. This will assist in identifying gaps and offer a roadmap for future research on thermal comfort in educational facilities. For an upcoming study, this article examines important shifts, advancements, and patterns in thermal comfort.

2. Methodology

The study selection and classification process in the document followed a systematic approach to ensure comprehensive coverage of thermal comfort research in educational facilities. Data was gathered using major academic databases such as Science Direct, Google Scholar, and library.uet.edu.pk. Keywords like thermal comfort, thermal comfort in classrooms, adaptive thermal comfort models, educational facilities, climatic classification, and regional studies were employed to identify relevant studies. The research was then classified based on several criteria. Regionally, studies were grouped into continents such as Europe, Asia, Africa, and the Americas, with a significant focus on Europe and limited attention given to Asia (outside China and India) and Africa. Climatic classification followed the Köppen system, which included cold, tropical, temperate, and arid climates, revealing a research bias towards colder regions.

Educational levels were another key classification factor, dividing the research into primary, secondary, and university classrooms. Most studies focused on university settings, followed by primary schools, leaving secondary classrooms as the least investigated category. The methodologies as shown in **Figure 4** used in these studies were also analyzed, with objective assessments (measurements of temperature, humidity, and air velocity) and subjective approaches (surveys) being the most common. Additionally, the review noted the frequent use of PMV-PPD models, though adaptive thermal comfort models were highlighted as more effective for capturing regional and cultural nuances.

Key findings include a need for increased research in tropical and arid climates, as well as in underrepresented regions like South Asia and Africa. Moreover, secondary classrooms require more focused investigation to address existing gaps. This analysis underlines the importance of adaptive models, retrofitting strategies for resource-constrained areas, and tailored research approaches to improve thermal comfort in diverse contexts.

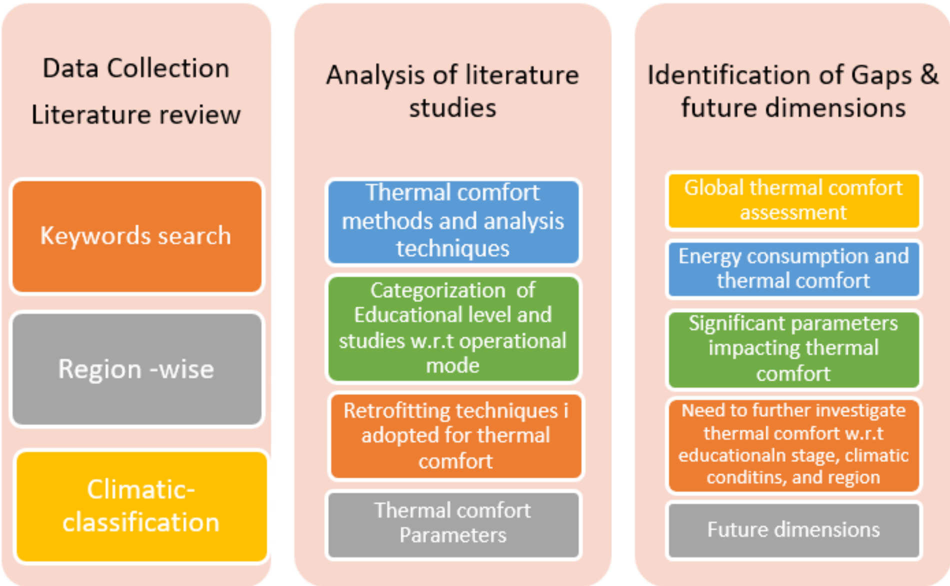

Figure 4. Schematic diagram of review.

By 2030, developing countries are expected to house 85% of the world's population [13]. The high density of people and the unpredictable outdoor temperatures during the transitional seasons lead to poor indoor comfort [14]. Moreover, different nationalities exhibit specific differences in thermal comfort temperature and thermal adaptation behavior, such that different adaptation models affect thermal comfort perception and thermal adaptation [15]. Physical and physiological differences should also be considered significantly. These may influence thermal regulation and perception based on distinctive contextual and geographical factors [16].

The search was further carried out by region-wise trend of thermal comfort studies for the last three years to understand the regional trends in the field of thermal comfort studies, and the trend shows that Europe, the USA, and Australia had produced the maximum number of research articles respectively, on contrary Asia and Africa had the least number of published articles in this regard. Although thermal comfort is a complex subject of discussion, it has multiple streams that make it more exciting and diverse to study its scope, which is not limited to one subject. It is most widely investigated in the energy domain, followed by engineering and environmental psychology. This sheds light on two main facts. One reason that this subject of thermal comfort cannot be researched in isolation is that it involves different domains of study very closely, i.e., energy, engineering, and environmental psychology, respectively. The categorization is based on the most significant publications in the relevant domains in the last three years.

Moreover, it is interesting that the trends of thermal comfort studies in the domains mentioned above are precisely analogous for all regions, i.e., Europe, the USA, Australia, Africa, and Asia. Additionally, a similar trend can be seen in most publications in the top three journals followed by all the regions mentioned above. This is depicted in **Figures 5–7**, respectively.

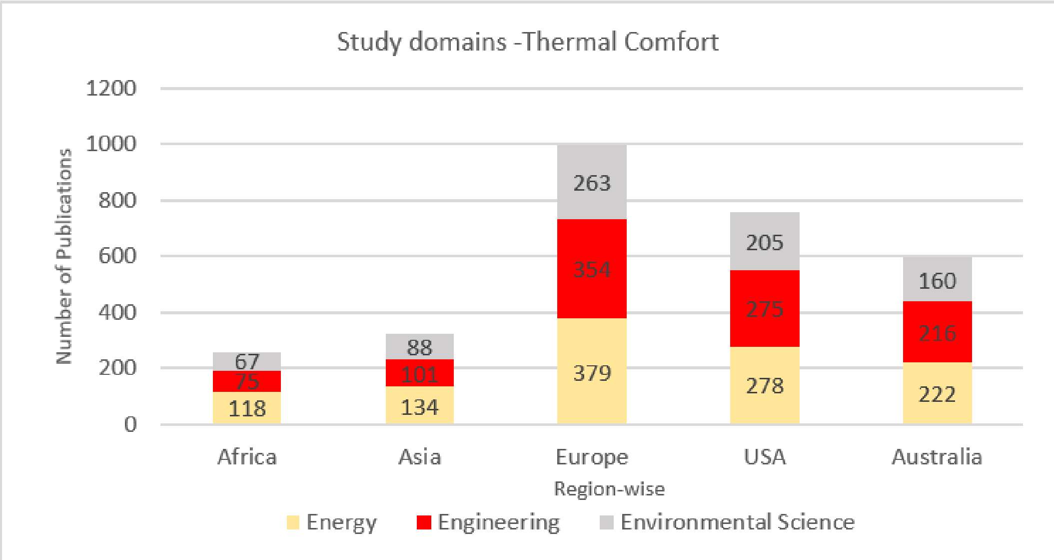

Figure 5. Most searched relevant research domains.

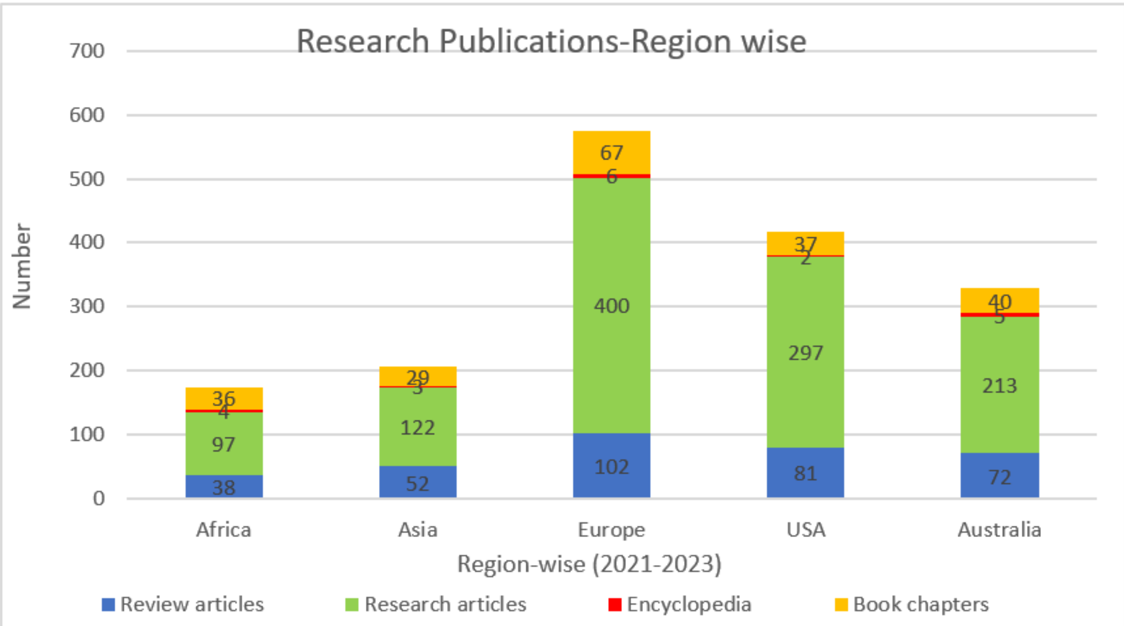

Figure 6. Number of published articles from 2021–2023.

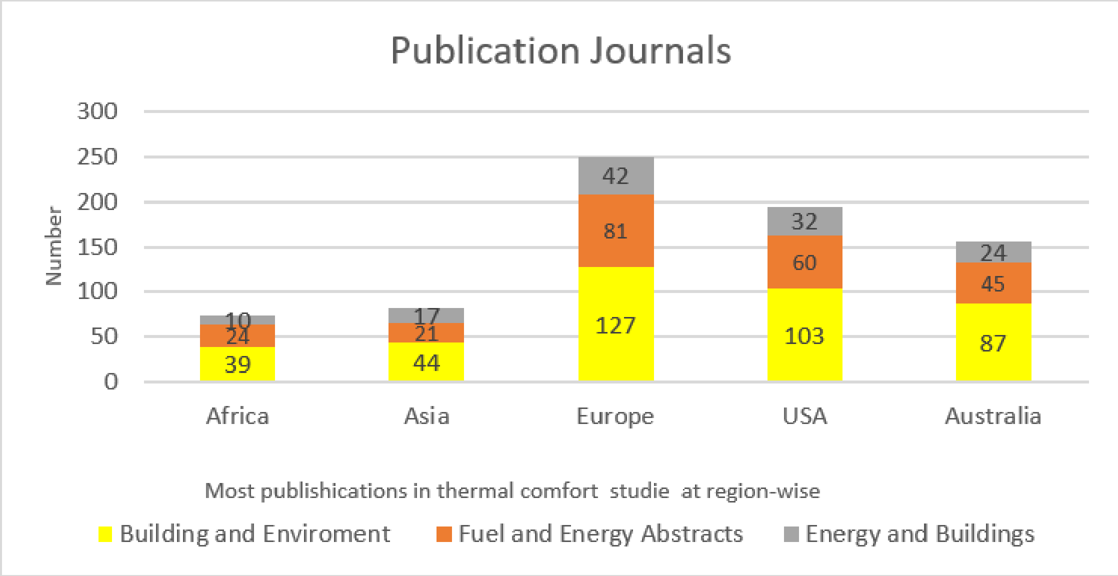

Figure 7. Publications in the top three journals.

2.1. Regional and climatic impact of thermal comfort

With the surge of climate change and the global push to become more energy efficient in all aspects of life, including building ventilation, thermal comfort has become a hotly debated issue. Due to climatic variations, there are differences in students' preferences for environmental temperature, and the highest allowable temperature, according to a meta-analysis study on human comfort and indoor environmental quality conducted between 1977 and 2009, is thermal quality [17]. The average temperature in the office was 25.4 °C, whereas the average temperature in the classroom was 22.8 °C [15]. On the other side, one of the researchers discovered that the neutral temperature for students in Taiwan's hottest month might reach up to 29.2 °C [18] higher than the ASHRAE Standard-55. (ANSI/ASHRAE) [19]. According to thermal comfort studies conducted in naturally ventilated classrooms in India, there are many neutral temperatures and comfort temperature ranges. The regression technique was utilized to determine 29 °C as the neutral temperature. When the operating temperature was between 22.1 °C and 31.5 °C, the thermal acceptability was greater than 80%. At an indoor air temperature of 29 °C, the logistic regression model predicts that more than 80% of ceiling fans will be used [20]. Additionally, women's heat sensitivity was consistently higher [21].

2.2. Impact of conducive classroom environment

The function of educational facilities in generating a constructive educational environment and promoting environmental consciousness has been increasingly recognized in recent years. As a result, various research studies on educational buildings have been conducted, demonstrating that poor interior environmental conditions have a detrimental impact on students' learning capacities and performance [8–11]. Furthermore, considering that students spend one-third of their time within school facilities [12,13], health and well-being concerns are of excellent study interest.

2.3. Thermal comfort studies in classrooms categorized based on education level climate classification

Classrooms are more congested than other workplaces, with an occupancy density of approximately four times that of office buildings [22]. It was found that the probability of absenteeism was 1.28-fold higher in high-exposure compared to low-exposure pupils [22]. Many studies have previously been conducted in various nations with various temperatures, emphasizing the relevance of comfort in interior settings [13–15]. Cold or heat stress can create thermal pain and diminish motivation to exert effort during work [16]. According to several research findings, many classrooms do not function as well as they could. According to various research findings, many classrooms do not operate as planned throughout the design phase in terms of their indoor environment conditions.

Previous studies demonstrate that more than 3000 articles were published focused on thermal comfort in classrooms. Various parameters were considered in these research papers more aspects were considered, the key words as shown in **Figure 8**, represent the most widely investigated terms in the last three years, including thermal comfort, thermal comfort in classrooms, thermal comfort in university classrooms, thermal comfort parameters in classrooms, thermal comfort in primary classrooms, and least investigated classrooms are the secondary ones. **Figure 9** depicts the trend of publications according to the Koppen-Geiger climate classification. Cold climates are most researched for thermal comfort studies, followed by tropical, temperate, and arid climates. It is pertinent to mention that the lowest number of publications were in climates. This stressed the need for further investigation in this domain. Similarly, **Figure 10** presents the same trend as **Figure 9** relevant to educational stage research for the last three years in more detail considering Koppen-Geiger climatic classification. **Figure 11** reveals trends of thermal comfort studies in the last three years for primary, secondary, and university classrooms.

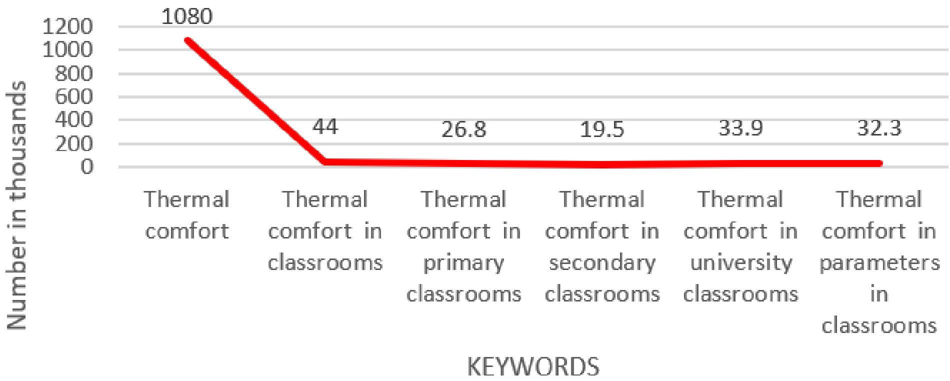

Figure 8. Thermal comfort studies in different educational levels keywords searched.

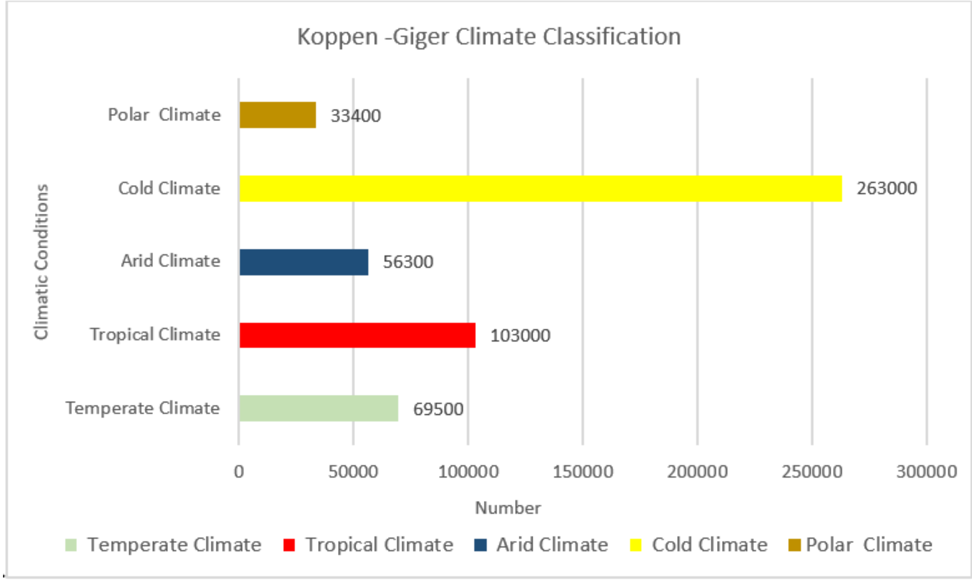

Figure 9. Thermal comfort studies in Koppen-Giger climatic classification.

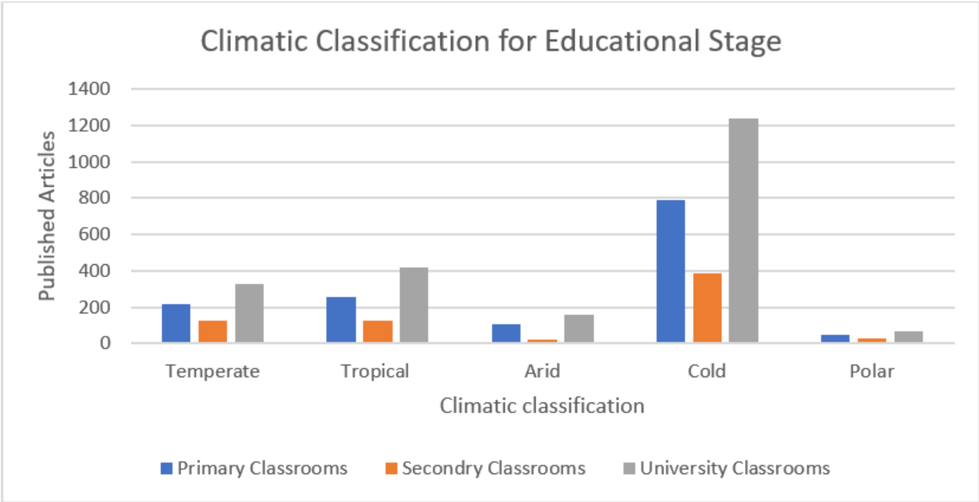

Figure 10. Thermal comfort studies in climatic classification for educational stage.

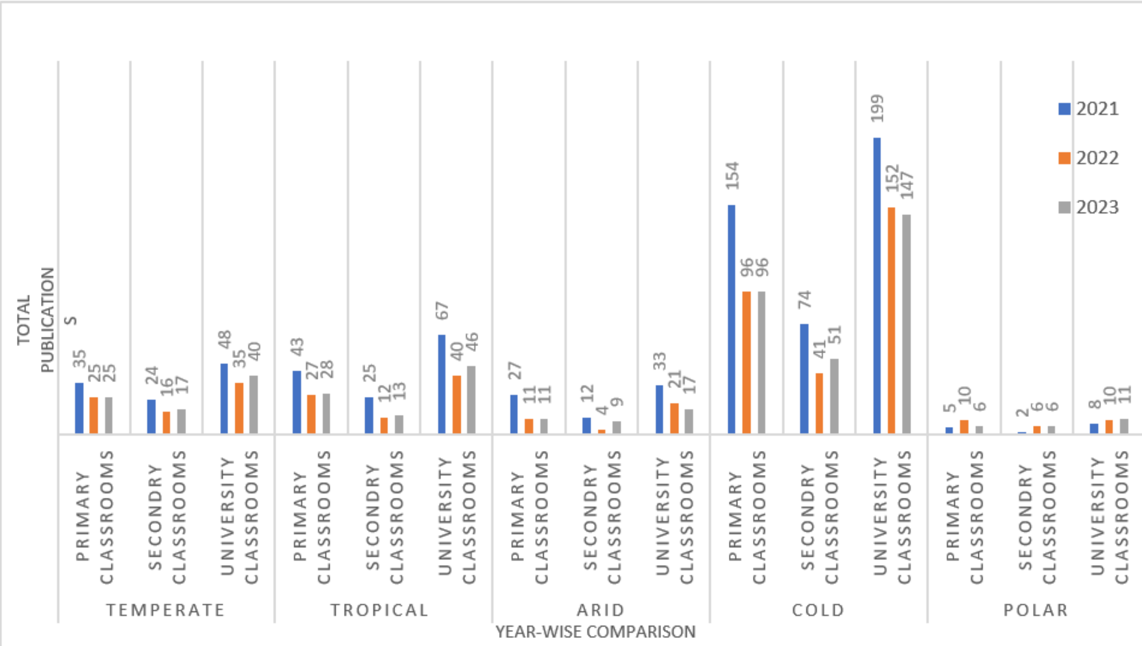

Figure 11. Publication year-wise comparison (2021–2023).

Table 1 Below are 30 research articles published during (2021–2023) specifying the country's educational level of the case studies, subdivided into three categories: Primary, secondary, and university classrooms. All the publications were classified based on the Köppen climate classification, which divides climates into five main climate groups, each divided based on seasonal precipitation and temperature patterns. The five main groups are A (tropical), B (arid), C (temperate), D (continental), and E (polar). Each group and subgroup are represented by a letter. In addition, all the published articles considered the thermal comfort assessment in naturally ventilated classrooms.

Table 1. Educational stage comparison of thermal comfort studies in classrooms.

No	Authors	Year	Country	Classroom	Climatic Group	NV	TC	Source
1	Aghniaey et al.	2019	USA	University	A	*	*	[23]
2	Fabozzi and Dama.	2019	Italy	University	C	*	*	[24]
3	Jindal.	2019	India	Secondary School	A	*	*	[25]
4	Korsaviet al.	2020	UK	Primary school	C	*	*	[26]
5	Nakagawa et al.	2020	Japan	Secondary School	C	*	*	[27]
6	Jowkar et al.	2020	UK	University	C	*	*	[28]
7	Alatalo.	2020	Pakistan	Primary school	B	*	*	[29]
8	Ma et al.	2020	China	Primary school	B	*	*	[30]
9	Korsavi and Montazami.	2020	UK	Primary school	C	*	*	[31]
10	Munonye.	2020	Nigeria	Primary school	A	*	*	[32]
11	Talukdar et al.	2020	Bangladesh	University	A	*	*	[33]
12	Bughio et al.	2020	Pakistan	University	A	*	*	[34]
13	Aparicio et al.	2021	Spain	Primary school	C	*	*	[35]

Table 1. (*Continued*).

No	Authors	Year	Country	Classroom	Climatic Group	NV	TC	Source
14	Wang et al.	2021	China	University	B	*	*	[36]
15	Kumar and Singh.	2021	India	University	A	*	*	[37]
16	Ikeda et al.	2021	Japan	Secondary school	C	*	*	[38]
17	Alonso et al.	2021	Spain	Primary Schools	C	*	*	[39]
18	Korsavi et al.	2021	UK	Primary School	C	*	*	[40]
19	Khambadkone et al.	2022	India	University	A	*	*	[41]
20	Aguilar et al.	2022	Spain	University	C	*	*	[42]
21	Torriani et al.	2022	Italy	Primary school	**C**	*	*	[43]
22	Hu et al.	2022	China	University	B	*	*	[44]
23	Lamberti et al.	2023	Italy, France	University	C	*	*	[45]
24	Riaz et al.	2023	Pakistan	University	B	*	*	[46]
25	Shrestha and Rijal.	2023	Nepal	Primary school	A	*	*	[47]
26	Bhandari et al.	2023	India	University	A	*	*	[48]
27	Torres et al.	2024	Spain	University	C	*	*	[49]
28	Wu and Wagner.	2024	China	Secondary school	B	*	*	[50]
29	Romero et al.	2024	Spain, Portugal	University	C	*	*	[51]
30	Mustapha et al.	2024	Nigeria	University	A	*	*	[52]

Note: *: Included in the study, NV: Natural Ventilation, and TC: Thermal Comfort.

3. Analysis and discussion for thermal comfort studies

Adaptive thermal comfort models are particularly effective in addressing the cultural and regional nuances of thermal comfort, making them more suitable than static PMV-PPD models in many cases. Unlike static models, which rely on fixed environmental parameters, adaptive models account for behavioral, cultural, and environmental adjustments that occupants make in response to their surroundings. These models recognize that comfort is not only a function of temperature but also influenced by local climatic conditions, building design, and occupant behavior. For instance, studies in naturally ventilated classrooms in regions like India and Bangladesh demonstrate that occupants tolerate significantly higher indoor temperatures than those predicted by static models, with neutral temperatures reaching up to 29 ℃ in some cases. This is attributed to acclimatization, cultural practices, and adaptive behaviors such as adjusting clothing, opening windows, and using fans. Similarly, research in transitional climate zones in China shows that the use of adaptive strategies, like ceiling fans and varied ventilation techniques, plays a crucial role in maintaining comfort. Adaptive models, therefore, provide a more realistic and inclusive framework for designing thermally comfortable spaces, especially in regions with limited access to mechanical HVAC systems. They also align with the goals of sustainability by promoting energy-efficient, human-centered building designs.

Thermal comfort studies are most widely investigated through subjective and objective assessments. The subjective assessments include field survey questionnaires that are either longitudinal or transverse. The objective assessment includes measuring environmental parameters such as temperature, humidity, air velocity, and skin temperature. Furthermore, the technique used for analysis was also studied in detail. It was found that traditional PMV-PPD by Fanger was most widely used alongside the adaptive thermal comfort model by Humphrey for thermal comfort assessment. **Table 2** summarizes the selected research articles' primary aims, methodologies, and findings.

Table 2. Research articles, methodologies, and findings.

Thermal Comfort study aim	Findings
With a focus on adaptive thermal comfort studies, this work employed a systematic approach to review the historical progression of thermal comfort research over the preceding century [53].	The adaptive regression-based methodology accounts for outside temperature variations and emphasizes human adaptation, while the heat balancing approach is distinct and essential to building and engineering system design.
This study set out to determine and prioritize the criteria, sub-criteria, and related indicators for assessing green building institutions in Malaysia [54].	The Malaysian government intends to use as little energy and resources as possible to provide a pleasant and healthy living environment by implementing a few associated rules and regulations based on the analytical hierarchical approach (AHP).
A dataset of interior temperature and relative humidity for low-income homes (field research) in five rural and urban locations has been created to close this gap. Indoor temperature readings were taken in villages in the Indian states of Maharashtra, as well as in Delhi (India), Dhaka (Bangladesh), and Faisalabad (Pakistan) [55].	The data set can be used to examine temperature and humidity variance in low socioeconomic level households in rural and urban areas to understand better the factors contributing to heat stress. It is essential to prepare and implement techniques to counteract heat stress. This information can be used to examine temperature variations in diverse types of homes and compare indoor and outdoor temperatures.
The current study assesses how students in Bangladesh's tropical-wet climatic zone perceive temperature and adjust behaviorally in NV University classrooms [33].	This study examines the degree of thermal comfort and coping strategies students use in naturally ventilated classrooms at Mymensingh University. It was discovered that students anticipate lower humidity levels and a more comfortable temperature in built surroundings. The high air speed seen throughout the study period decreased the discomfort brought on by high humidity.
This study used many characterization methodologies to determine thermal comfort zones (TCZ) in thermally dissatisfied individuals. Regression analysis is the analysis technique employed [56].	The American Society of Heating, Refrigerating, and Air-Conditioning Engineers—ASHRAE (2017) recommended winter temperatures of 23–26 C for all thermal comfort zones. This indicates the possibility of energy savings while preserving thermal comfort.
This paper proposes an India Model for Adaptive Comfort, or IMAC, based on the field surveys [57].	One important conclusion of the IMAC study across the three types of study buildings is that Indian office residents are more tolerant and adaptable to warmer temperatures. The analysis reveals that Fanger's static PMV model overpredicts the warmer side of the 7-point feelings scale.
The Hot Summer and Cold Winter (HSCW) zone of China's Zhejiang Sci-Tech University (ZSTU) provided the experimental environments for this study, which were created using three popular teaching modalities [14].	The ability of each test item to determine learning efficacy under the natural conditions of the transitional season varies depending on weather patterns and classroom settings. In the natural conditions of the seasonal transition, the relationship between the LP, the TSV, and TAV was linear.
By highlighting the shortcomings of the existing research on thermal comfort and proposing innovative directions for investigation into the integration of human-environment interactions, this review of the literature aims to bridge this gap [11].	The results indicate that it is critical to thoroughly assess the potential relationships between HVAC systems, the building envelope, thermal comfort, and their effects on energy consumption.
This study examined the perceptions and adaptive behavior of children in Dehradun, Uttarakhand, India, primary school classrooms without air conditioning during the summer and winter [58].	This emphasizes how appropriate it is to implement widely utilized TSV-based techniques for identifying the thermal comfort range of children in classrooms, particularly during hot weather. The findings of this study should assist local authorities and governments in making well-informed assessments about future initiatives to lower the dangers associated with children being exposed to heat.

Table 2. (*Continued*).

Thermal Comfort study aim	**Findings**
The main objective of this field study is to examine the optimal temperature ranges, low rates of SBS, comfortable surroundings, and productive work for male and female students in university classrooms [44].	Additionally, it was shown that the appropriate temperature ranges for men and women were 17.3-22.0 C and 18.5-20.8 C, respectively, and that fewer than 30% of the individuals overall reported feeling cold, performing poorly at work, or displaying symptoms of SBS. To ensure that participants are highly motivated to work, the optimal indoor temperature should be greater than 20.3 C for males and 20.4 C for women.
Current state of knowledge about productivity and thermal comfort is assessed [59].	The findings of the study were as follows: i) A broader spectrum of temperatures can be used to achieve performance and productivity; (ii) The majority of research uses a mix of methods or subjective measurements to assess productivity; and (iii) very few studies offer productivity evaluation algorithms.
This study discusses the architectural design elements of buildings that lower energy usage and suffer from heat. For analysis, Monte Carlo (MC) and LHS techniques are employed [60].	Simulation approaches can be used to optimize the elements related to architectural design. The important variables identified by this study will be immensely helpful to designers in the future. Additional research on thermal comfort and its impact on occupant performance is also necessary.
This study investigated the association between the efficiency of natural ventilation and the perception of heat felt by university students in the winter [42].	Conclusions indicate that to modify ventilation methods, the window opening mechanism must be changed. Based on the study's findings, it is determined that to prevent the percentage of dissatisfied students from rising above 20%, a temperature differential of no more than 2 to 4 C is required. Therefore, further steps should be taken in the middle of winter to create a secure environment that promotes kids improved academic performance.
This study uses fuzzy comprehensive evaluation (FCE) as its analytical tool [61].	Comparisons between the actual and expected findings show that PMV underestimates comfort temperatures at higher temperatures. Therefore, alternative thermal comfort study methodologies based on questionnaire surveys are required if these methods are appropriate for hot and humid nations like Malaysia.
This research is to gain a deeper understanding of the independent effects of each IEQ component, such as temperature, and to examine how residents' adaptive behaviors and the physical environment influence their perceptions of the many sub-factors [62].	The interaction of the ambient factors was not considered in the current work. An important project is to investigate how the four ambient variables interact multisensory and affect the quality of the indoor environment. Future studies ought to investigate the relationships between the overall effects of environmental factors and indoor environmental quality.
About conventional models of thermal comfort, a well-known research problem has been raised by this work: Models that rely on foundational data have not always been able to predict actual thermal comfort measurements from independent field studies accurately. To quantitatively predict subjective thermal comfort as a function of both thermal and non-thermal parameters of IEQ, this paper will evaluate a Bayesian logistic regression [63].	This new study will consider the changing seasons as one critical component, and field data will be collected in the summer and winter. The new IEQ study will employ updated technologies under the auspices of more current indoor building settings and building systems, in contrast to the COPE field survey conducted in the early 2000s. To cross-correlate thermal comfort with non-thermal IEQ requirements, the authors additionally demand that more data be gathered and assessed. Statistics based on Bayesian inference may still be helpful.
This study aims to understand students' thermal perception better, ascertain the thermal comfort and adaptation of the same respondents, and provide a scientific basis for developing classroom temperature control. The architecture design classroom is a specialized teaching and learning environment [15].	The same respondents' thermal comfort and adaptability were assessed using the PMV-PPD approach. Of course, in addition to thermal comfort, future research should consider other factors of building energy efficiency, like the building envelope.
To investigate how residents' adaptive behaviors and the surrounding physical environment affect their subjective feelings. In this work, the analysis tool is the FCE-AHP approach [14].	An overview of prediction equations based on multiple earlier studies that link environmental elements to pleasure. Numerous environmental elements work together to affect the quality of the indoor environment.
A literature survey and a subjective investigation will determine AHP weighting schemes [17].	Subjective surveys customized for each situation continue to be the best method for choosing suitable weighting schemes.
To determine whether various modifications to the interior environmental settings of the classrooms have a favorable impact on the perceptions and performance of the students through correlational analysis [18].	Students' perceptions of their cognitive performance were positively impacted by the reverberation time (RT) lowering. Lower reaction times (RT) and higher horizontal illuminance (HI) enhanced students' internal responses, learning quality, and perceptions of the lighting environment.

3.1. Energy saving techniques to attain thermal comfort

According to Dixon et al. [64], retrofit methods should include energy use, water usage, and waste generation. Light-touch retrofits might save up to 30%–40% on annual energy costs. Moreover, recycling water and garbage (for example, in shopping malls, offices, schools, and public buildings) might influence sustainability and cost. Additionally, Dixon et al. [64] study from the United Kingdom and the Institute for Building Efficiency [65] research from the United States indicates that the following retrofit measures are the most prevalent in the commercial property sector: Energy-efficient lighting and controls; Management systems and controls; and Building services. However, Kok et al. [66] discovered that there are other more expensive modifications and retrofitting steps that might be done to existing structures, such as replacing roofs, adding PV solar cells, altering flooring, insulation, and operable windows, or improving glazing systems. This relates to building thermal comfort, making the area more usable, and improving space productivity. Khalid [67] provided a comparative analysis using various HTCMs with a weather profile of Karachi, Pakistan. Their comparative analysis aids in identifying similarities in effective design methods. Architectural orientation, natural ventilation, and envelopes were discovered to be the most practical approaches for Karachi's hot, humid climate. Traditional passive house strategies are still widely used in the Karachi design of climatically responsive buildings. Khan et al. studied thermal comfort through double low-E electro-reflective glass and concluded that an 8.6% reduction in cooling energy demand and reduced indoor temperature could be achieved [68]. Researchers have used the Inductive methodology and Simulation model method. Retrofitting strategies include outer wall insulation of 0.05 m of EPS ACH Reduction from 0.7 to 0.3 along with usage of Low E double-glazed windows and metal louvers of 0.5 m [69]. The energy usage was reduced from 3800 W h/m^2 to 2900 W h/m^2 in Tanta University, from 6700 W h/m^2 to 3200 W h/m^2 in BHI and from 4700 W h/m^2 to 3200 W h/m^2 in AAST.

Taherkhani et al. evaluated that Insulating, windows, and heating systems changing or refurbishing were on most decision-makers retrofit list. For energy simulation analysis, building modeling visualization, and applying optimization methods, Energy Plus, Design Builder, and MATLAB are more common, respectively. They reviewed 153 different research papers [70]. A group of scientists examined the efficiency of using passive cooling techniques using BIM. Results show that implementing passive cooling techniques in a building with an estimated payback period of 3 years and 2 months can lower the annual energy consumption of a particular building by up to 35% [71]. Replacing old air-conditioning and cooling appliances with new ones results in an estimated decrease of 25.01% per day. The estimated net payback period for retrofitting is 6.30 years for air-cooling and air-conditioning load and 1.95 years for lighting [72]. Schwartz et al. [73] studied energy retrofit and IEQ improvement strategies to address conflicts between energy efficiency and IEQ. He found the relative impact of stock-wide variables on the performance criterion in a pair-wise scenario (the baseline is a classroom in a pre-1918 London neighborhood in 2020). Red: 80% to indicate a percentage change in the "wrong direction", Green: 80% to indicate a percentage change in the "right direction", and white: 0% to show no change (with varying shades of red, green, and white in between) [73].

To combat the challenges of climate change, reduction in energy consumption and, without compromising, the attainment of thermal comfort in buildings is becoming a significant issue over time. This leads to the implementation of retrofitting techniques in existing buildings and thermal insulation for future development to achieve a sustainable built environment.

3.2. Thermal comfort parameters

3.2.1. Building occupants

The performance discrepancy resulting from both controlled and uncontrollable elements is attributed, in part, to occupant behavior [74]. For example, Hong and Lin conducted simulation research to demonstrate that, in comparison to normal assumptions, occupant behavior at the office size might raise energy use by 80% or decrease it by 50% [75]. More than 130 times as much is spent on employee remuneration when low indoor environmental quality is the cause [76]. Augenbroe and Ruya have investigated how people perceive a heated environment about activities, clothing, age, gender, and mental health. He discovered that low-energy buildings behave differently from typically planned residences in terms of the thermal indoor environment [77]. The newly developed model's dynamic variation of physiological factors, such as the behavior of the human body, is compared to results obtained using standard set-point values of relative humidity and air temperature (20 ℃, 45% for heating requirements and 26 ℃, 50% for cooling requirements) [78].

3.2.2. Regional impact

It is anticipated that 85% of the world's population will be living in developing nations by 2030 [13]. Poor indoor comfort is caused by the transitional seasons' high population density and erratic external temperatures [14]. Additionally, the thermal comfort temperature and thermal adaptation behavior of different nations vary, and the thermal comfort perception and thermal adaptation of students will be influenced by a variety of adaptation models [15]. In addition to the ways that physical and physiological variations may affect how heat is regulated and perceived, unique contextual elements should also be considered [16].

3.2.3. Building design parameters

The study found that ABDPs, such as cooling set-point temperatures and roof design, can significantly reduce the operative temperature by as much as 20 % and 14.2%, respectively. These reductions in thermal discomfort hours could result in energy usage reductions of 43.7% and 41.0%, respectively [60]. Corvacho and Oliveira have investigated the effects of shade and glazing on thermal comfort. The sun travels at a high angle throughout the summer, and the classroom cantilever protects the glazing from solar radiation during its peak, preserving it above permissible limits when compared to office building windows [79].

3.2.4. Environmental parameters

Tang, et al. talked about productivity, Comfort temperature, and air quality. The results showed that, with 76.9% of comfort votes varied, students' average comfort vote was cool. The ASHRAE comfort range (20.0 ℃–26.0 ℃) is preferred by students [80]. A few scholars have examined how to measure the thermal comfort of courtyards. Since Iraqi courtyards are uninviting for about two-thirds of the year's working hours, various passive and active solutions must be created [81]. The relationship between humidity and thermal comfort was also investigated, and it was shown that there is a similarity in the indoor humidity and temperature measurement pattern when the temperature and humidity of space are changed, but in the change of the temperature and humidity of the living body, the change in humidity showed a lot of difference for each person [82]. In Malaysia, most people feel most comfortable in their offices when the air temperature is between 20 ℃ and 28 ℃ and the humidity is between 40 and 60%, according to a survey conducted by the Department of OSH. For air circulation, it is advised that everyone breathes ten l/s of fresh air [83]. The reason for the need was COVID-19. As a result, most educational institutions were offering remote instruction from their offices, necessitating improved office thermal comfort. Additionally, the occupants' needs are not met by the outdated HVAC system [84]. The analysis's conclusions indicated that the acceptable temperature was between 22.5 ℃ and 26.5 ℃, with the operating temperature of thermal neutrality being 25 ℃ [85].

3.2.5. Personal parameters

Furthermore, variables related to personal information, including gender and age, particularly in the 16–25 age range, are more commonly employed as a study context or to arrive at conclusions regarding thermal perception. In addition to feeling noticeably colder than their male counterparts in the same thermal setting, women also consistently showed increased thermal sensitivity [21]. ISO 7730 advises that occupiers adapt their apparel to a value of 0.5 Clo in the summer and 1 Clo in the winter [86]. One of the other things to take into account is the insulation of the clothing and the chairs that the people were sitting on [57,63]. Zeeshan, et al. are also looking at the effects of gender on thermal comfort. The calculated comfort temperatures for male and female residents throughout the summer and winter, respectively, were 26.4 ℃ and 27.8 ℃, using the liner regression approach. The mean operative comfort temperatures for male and female residents in the summer and winter were determined to be 26.8 ℃ ± 1.5 ℃ and 27.6 ℃ ± 1.7 ℃, respectively, using Griffth's approach [87].

3.2.6. Productivity

Inadequate indoor environmental factors can have a detrimental effect on students' academic performance and lead to health issues. Examples of these situations include high room air temperatures, noisy classrooms, low lighting, and poor indoor air quality [58]. The phrase "presenteeism" was first used by the UK Centre for Mental Health. It describes workers who show up for work but do not produce as much. One of the main causes of the decreased productivity in the built environment industry is presenteeism. In the UK, it results in a £15 billion annual loss [88]. Numerous earlier research has demonstrated that the IEQ has an impact on human comfort, efficacy, productivity, health, and satisfaction [89].

3.2.7. SBS

Another essential aspect that will impact productivity and energy efficiency is sick building syndrome (SBS), which can emerge in a group of individuals because of unhealthy building conditions. Lethargy, headaches, runny or clogged noses, dry eyes, sore throats, and occasionally dry skin and asthma are just a few symptoms that users may experience [89]. Moreover, gender disparities have an impact on the occurrence of SBS symptoms in buildings [44]. Headache, tiredness, strained eyes, wheezing, dry throat, coughing, tension, memory loss, dry or itchy skin, nausea, and upset stomach are common [90].

3.2.8. Ventilation

With only 12% of educational buildings using mechanical or hybrid ventilation, natural ventilation is the most popular type of ventilation system in the US, Southern and South-Eastern Europe, China, India, Australia, and the UK [22]. It is simple to see behavioral adaptation in daily life, which may be further divided into three categories: Cultural reactions (like taking a siesta), personal adaptations (like changing clothes), and technical adaptations (like turning on and off a fan or air conditioner) [86]. Furthermore, long-term sustainability objectives and energy reduction are better served by naturally ventilated (NV) classrooms [91], propagation of airborne diseases, especially in crowded interior environments like classrooms [92]. The architectural style, defined by the type of material used and how the walls and roofs are constructed, ventilation, interior and exterior shading, and cooling systems, are additional factors to consider besides the external weather parameters [55]. **Figure 12** below shows the crucial factors that should be considered to enhance thermal comfort and, in turn, building performance.

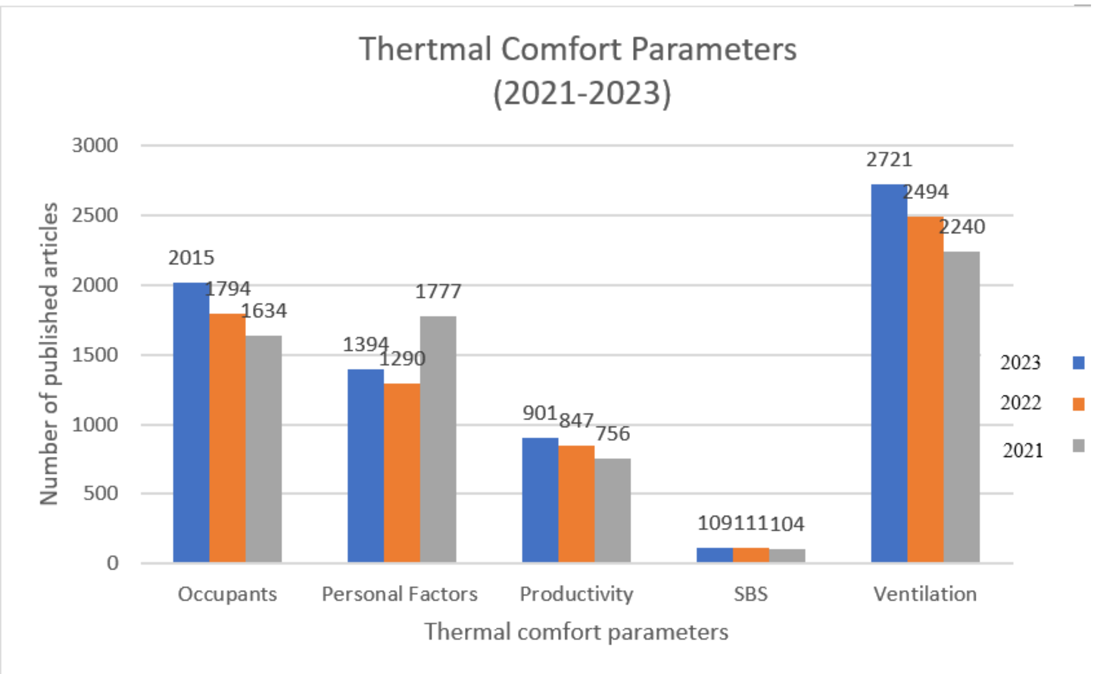

Figure 12. Thermal comfort parameters.

3.2.9. Other parameters

Yu et al. have reported on factors significantly influencing building energy use. Climate, occupants' behavior, building-related, user-related, building services operations, indoor air quality, and social and economic issues [89]. The effects of architectural building design parameters (ABDPs) on occupant thermal comfort and energy consumption were studied. These parameters included window-to-wall ratio, cooling set-point temperature, heating set-point temperature, building rotation, external wall construction, roof construction, glazing type, local shading type, occupancy density, mechanical ventilation rate per area, thermal mass, roof window openings, building location, infiltration and crack level (airtightness), were identified and their effects on occupant thermal comfort and energy consumption were studied [60]. The architectural style, defined by the type of material used and how the walls and roofs are constructed, ventilation, interior and exterior shading, and the use of cooling systems, are additional factors to consider in addition to the external weather parameters [55]. Since the changes in the thermal quality of the learning environment have an impact on students' academic performance as well as their physical and mental health, it is imperative to assess these new indoor environmental conditions [42]. Other crucial factors are energy costs, reduced peak demand, and thermal comfort. The TABS envelope operates at a temperature that falls comfortably within the 90% adjustable comfort zone, according to ASHRAE guidelines [93]. Analysis and comparison of empirical data from many field surveys on thermal comfort carried out in Korean with reference data acquired using the original English version of the ASHRAE scale [94]. The finding that building occupants in Europe are more sensitive to temperature variations than those in other locations leads to the conclusion that the adaptive model connection serves as the foundation for the adaptive comfort standards [95].

4. Conclusion and way forward

According to the above literature review, the residential sector building is the most researched in the context of the thermal comfort field. This calls for attention to investigation in other building types, such as the educational and hospitality sectors. Thermal comfort studies are researched in different domains, primarily in energy and then in engineering, while the lowest number of articles are published in environmental psychology.

These different domains make thermal comfort complex to understand. In addition, its dependence on geography, climate, culture, personal perception, and preferences of the users in different regions adds to further difficulty and variable subjective and objective responses. The educational stage research further emphasizes that investigations were conducted on the thermal comfort of university and primary classrooms, but a considerable gap lies for secondary stage classrooms. Classrooms are a critical component of educational facilities. A comfortable indoor thermal environment enhances learning efficiency and productivity and improves health conditions. The present research focused on the regional, climatic, and educational stage research implications in educational facilities where students spend their maximum time.

Regarding regions, the maximum amount of research was conducted in Europe, but further investigations in the Asia and Africa regions are required. The south-Asian region is most neglected apart from China and India, and a few research were found for Pakistan, Bangladesh, Sri Lanka, and Nepal. According to Koppen-Geiger, climate classification is in cold regions, and the least searched is in polar regions. These trends are quite similar for regional and climatic classification. Various research methods are used to assess thermal comfort. Traditional PPD and PMV Models are used most widely along with adaptive thermal comfort models, and the latter is more effective in investigating regional and cultural contests. Thermal comfort is associated with objective and subjective evaluations in the climatic chambers and field studies. The latter presents a more realistic assessment of the users' comfort level. Numerous factors affect thermal comfort. According to research articles published in the last three years, ventilation is considered the most prominent factor, followed by building occupants, personal factors, and productivity, and the least researched area is sick buildings syndrome SBS, which is related to the health conditions of the students.

The above research also highlights that developed nations are more concerned about attaining thermal comfort than developing countries. It is pertinent to mention that retrofitting is the most efficient technique to make buildings more energy-efficient and environment-friendly, but it is a costly measure for developing nations to adopt for existing building stock. Although the energy crisis, economic constraints, and climate change are global problems, all nations should play their role effectively and efficiently to combat these issues. Substantial world populations are expected to reside in developing countries so the thermal comfort assessment will lead to energy and resource conservation.

Following are the recommendations for stakeholders in developing countries to address the challenges of achieving thermal comfort in educational facilities. First, stakeholders should prioritize the adoption of adaptive thermal comfort models that align with local climatic and cultural contexts. These models are particularly suitable for naturally ventilated buildings, offering cost-effective and sustainable solutions for regions with limited resources. Second, the implementation of affordable retrofitting techniques such as low-cost insulation, reflective glass, and natural ventilation enhancements should be encouraged to improve the thermal performance of existing buildings. Local construction teams should be trained in these techniques to ensure widespread and efficient adoption. Third, the design of educational facilities should focus on human-centered approaches, incorporating features such as operable windows, passive cooling techniques, and shading devices to minimize reliance on mechanical systems.

Additionally, stakeholders should develop region-specific thermal comfort guidelines based on extensive field research that considers local climatic conditions, occupant behaviors, and cultural practices. This requires collaboration between researchers, policymakers, and building designers to create comprehensive and practical solutions. Capacity-building programs such as workshops and training sessions for architects and engineers are essential to promote awareness and expertise in sustainable building practices. Moreover, governments in developing countries should integrate thermal comfort principles into national building codes and standards, mandating their application in new constructions and renovations of educational facilities. Lastly, international collaboration should be leveraged to access funding, advanced technologies, and technical expertise, enabling developing countries to implement innovative thermal comfort solutions effectively. These recommendations aim to create thermally comfortable, energy-efficient, and sustainable educational environments in resource-constrained regions.

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