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Review Article

Critical Review of the Literature on Thermal Comfort in Educational Buildings: Study of the Influence of the COVID-19 Pandemic

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Thermal comfort in educational buildings affects not only the well-being of students but also their academic performance. Over time, various methods have been developed to assess it. However, none of them takes into account the adaptation of students of different ages, which is an important issue. In recent years, the study of thermal comfort has become very important due to energy-saving measures and ventilation protocols to combat the spread of the SARS-CoV-2 coronavirus. Therefore, it is necessary to gather all the information to guide future research. Thus, this paper presents a comprehensive review of field studies on thermal comfort in classrooms at different educational levels. The focus is on those conducted during the global pandemic of COVID-19. It has been observed that students from climates with a higher degree of variation have shown a better adaptation. Children also tended to feel less affected by changing temperatures. High school and university students showed a greater range of dissatisfaction with heat than with cold. The adaptive approach is more suitable for recognising the comfort needs of all age groups. However, by using this approach together with the Fanger method, more reliable results have been reported. In most of the studies, comfort levels were found to be lower than those indicated by the standards, highlighting the need for guidelines adapted to the thermal comfort conditions of all students. Finally, the various natural ventilation measures to avoid COVID-19 infection have led to a decrease in comfort levels, especially in winter.

1. Introduction

Thermal comfort in educational buildings not only affects the comfort and well-being of students and teachers. It also has a direct impact on their health and academic performance [1, 2]. However, such buildings sometimes struggle to maintain comfortable conditions conducive to the learning process [3]. Factors such as the orientation of schools, architectural design, heating, ventilation, and air conditioning (HVAC) systems, as well as the interactions between occupants and the built environment, are key to achieving optimal thermal conditions [4–6], especially in a context where climate change is leading to an increase in extreme energy events [7]. At the same time, rising energy prices and growing concerns about energy security have recently increased the importance of this factor [8, 9]. For these reasons, it is necessary to study and improve the energy efficiency of buildings, trying to achieve a balance with the thermal comfort conditions in the interior spaces [7].

At the same time, given the amount of time students spend in classrooms, it is essential to ensure an environment that promotes conditions conducive to concentration, attention, and effective learning [10–12]. Students may spend several hours at a time in these enclosed spaces during a typical school day [13, 14]. Inadequate thermal conditions can therefore have a cumulative negative effect on their well-being and performance throughout the day. However, when thermal conditions are optimal, students can focus on educational activities without weather-related distractions [15]. An indoor environment characterised by comfortable and balanced thermal conditions contributes to a state of general well-being, which is also reflected in increased engagement and participation in the educational process [16].

Several methods have been developed for the assessment of thermal comfort [17], with the rational Fanger or thermal equilibrium model (PMV and PPD indices) [18] and adaptive models [19–21] being the most widely used in the scientific literature. However, in the case of educational buildings, relevant issues arise when considering the adaptation of students at different levels of education. On the one hand, it is important to recognise that the adaptive capacity of students may vary, especially at the lower levels of education where teachers play a key role in actively modifying the thermal environment [22, 23]. It should also be noted that thermal perception may differ between children and adults, so it would be appropriate to consider individual pupil preferences when designing classrooms to improve thermal comfort and optimise the learning environment [24]. At the same time, a variety of activities take place in educational buildings that can influence the assessment of thermal comfort. In particular, activities with higher metabolic rates, such as physical activity, participation in dynamic lessons or laboratory exercises, and movement between different spaces in educational buildings, can lead to an increase in body heat production and affect the thermal perception of occupants [25, 26]. Finally, it is important to study the interaction between environmental conditions and students' clothing, as this can affect their thermal sensation and ability to regulate their comfort [27].

The extent to which a thermal environment study can identify detailed adaptation mechanisms depends largely on the accuracy of in situ physical measurements and subjective questionnaires [23, 28]. These questionnaires focused on questions relating to thermal sensation and preference. More recent research has increasingly included such questions on humidity and air velocity. At the same time, it is essential to include questions on preferred coping strategies, information on clothing and position in enclosed spaces, activities undertaken [29–31], and aspects related to students' health and performance [32–34]. However, there are still no methodological mechanisms to establish the duration of surveys or the optimal number of respondents for the assessment of thermal comfort in educational buildings. In contrast, recommendations have been made to simplify and adapt thermal questionnaires for younger children to ensure the adequacy of the data collected in this population [23, 35].

It is also important to note that indoor air quality also plays a crucial role in the thermal comfort and health of occupants in educational buildings [4, 36–40]. This factor has become particularly relevant in the global pandemic scenario for COVID-19 [41–47]. A good air quality environment is essential to reduce the risk of virus transmission, as well as helping to mitigate the effects of allergies and general discomfort. This involves adequate ventilation that promotes air renewal, particle filtration, and pollutant removal [48, 49]. However, it is important to strike a balance between ventilation and thermal comfort, as excessive increases in ventilation can lead to a feeling of discomfort among occupants [41].

Furthermore, as buildings aim to combine energy efficiency and comfort, it is important to study and understand how the level of thermal comfort can affect the energy consumption of buildings and to look for solutions that improve both efficiency and the well-being of the occupants [50, 51].

The complexity of educational environments, coupled with the lack of specific standards for thermal comfort in such buildings, has necessitated the use of standards such as ISO 7730 [52], ASHRAE 55 [53], and EN 15251 [54] as reference documents. These standards are primarily based on data collected in laboratories [52] or field studies conducted in offices with healthy adults at steady state, where clothing and activity levels are assumed to be constant [55–57]. However, given the characteristics of educational spaces, these standards appear insufficient to ensure comfortable conditions for students and teachers, as they do not take into account individual student preferences [23]. They also do not take into account current contexts where indoor air quality and energy efficiency are given priority.

Based on the above, thermal comfort in educational buildings at all levels has been the subject of extensive research, using various models and indices with the aim of understanding and improving this area of study. However, despite the efforts made, there are still challenges that, although identified in the available scientific literature, have not yet been resolved. Therefore, it is recognised that there is a need for a systematic collection, classification, and analysis of these studies to assess the current state of research and identify current issues and situations. This paper is aimed at filling this gap by highlighting current problems in thermal comfort studies in educational buildings. To carry out this work, an exhaustive literature review of field studies of thermal comfort in classrooms at different educational levels published in peer-reviewed scientific journals and international conference proceedings over a period of the last 25 years will be carried out. Based on different characteristic parameters, the collected information will be sorted, compared, and contrasted. In addition, the impact of the COVID-19 pandemic on the field will be analysed, and how the situation created by the pandemic has affected research on thermal comfort in classrooms will be examined, considering possible changes in approaches, priorities, and challenges faced by the scientific community.

2. Materials and Methods

2.1. Research Methodology. The selection process of scientific publications for this work is based on the methodology adopted in the JBI Manual for Evidence Synthesis [58, 59]. Based on this manual, a complete literature review is commonly associated with the following steps: (1) delimitation of the search scope; (2) synthesis of the search strategy; (3) definition of the literature database, search rules, and selection criteria; (4) search in the selected databases; and (5) final selection of publications.

Table 1: Logic grid and keywords.

Thermal comfort	Educational building	Field study
"thermal comfort" OR "thermal sensation" OR "thermal preference" OR "thermal acceptability" OR "thermal conditions" OR adaptive AND "thermal comfort" OR Fanger AND "thermal comfort"	school* OR "primary education" OR "secondary education" OR universit* OR "higher education" OR pupil* OR student* OR classroom*	survey* OR investigation* OR stud* OR assessment*

2.1.1. Scope Delimitation. The main objective of this paper is to provide a detailed overview of research on thermal comfort in educational buildings at all levels over the last 25 years. Therefore, this review will focus on (a) educational buildings of primary and secondary education as well as universities. It excludes outdoor environments of these buildings, kindergartens, and different types of centres where other types of training courses are provided; (b) thermal comfort in these types of buildings, excluding works that exclusively study other forms of comfort, such as visual, acoustic, or ergonomic; (c) the assessment of thermal comfort using the rational and adaptive approach; and (d) field studies on thermal comfort, excluding literature reviews.

2.1.2. Synthesis of the Search Strategy. After defining the scope of this literature review, it is necessary to convert the search criteria into instructions that can be interpreted by the databases. Table 1 shows the keywords used, followed by the respective alternative terms. The search digest was formulated taking into account the basic Boolean operators (OR, AND, and NOT) and modifiers (e.g., asterisks for truncation, when different forms of the word are valid and inverted commas, indicating when phrases should be kept together) [60].

2.1.3. Definition of the Literature. The databases selected for this study were Scopus, Web of Science, SAGE Journals, and PubMed, as they cover most of the literature in the fields of engineering and architecture, as well as health and social sciences, and allow for a comprehensive subject search. On the other hand, only literature published in peer-reviewed journals and international conference proceedings was reviewed in this paper. In addition, as mentioned above, we included papers published in English in the last 25 years (1998-2023) to assess the most recent research on the topic.

To select papers that deal exclusively with field studies of thermal comfort in educational buildings, this systematic review focuses on typical teaching classrooms, excluding laboratories, gymnasiums, and classrooms with special features.

2.1.4. Searching in Databases. The search in the different databases was carried out in April 2023. The keywords listed in Table 1 were used in the titles, keyword lists, and abstracts of the publications. Initially, 879 publications were identified in Scopus, 746 in Web of Science, 38 in SAGE Journals, and 12 in PubMed. Many of these results were duplicates and were subsequently eliminated, leaving 309 publications. All abstracts of the search results were read using the selection criteria mentioned in section 2.1.1. If they met the marked requirements, they were selected to pass the full-text filter. This process resulted in the selection of 238 articles.

2.1.5. Final Selection of Publications. The subsequent screening involved a thorough content analysis of these 238 publications, i.e., not only the title, keywords, and abstract but also the full text of the articles. After a detailed reading of the entire content, we eliminated those papers that did not show any signs of exclusion in the titles, keywords, and abstracts but were still excluded from the study after a thorough review. In this way, 189 papers were selected. At the same time, this process included a second search of the reference lists of the accepted publications to identify related papers that had not appeared in the first database search. In this way, 34 articles were added to the list for full-text screening. This resulted in a total of 223 publications in the final assessment. Figure 1 shows the literature search procedure carried out for this study.

Finally, it should be noted that the PRISMA 2020 statement has been used, which includes a checklist of 27 recommended points for the writing and publication of systematic literature reviews, to standardise the information presented based on evidence and increase the transparency of this research [258, 259].

2.2. Field Study Methodology. The main objective of this research was to identify and discuss the main factors affecting thermal comfort in educational buildings, through a critical review of previous research, considering the guidelines set by the various norms and standards.

Firstly, a statistical analysis of the articles reviewed was carried out to understand recent trends in this field of research. To this end, we studied the number of papers published according to year, country, and journal or international conference proceedings. Likewise, an analysis of the cooccurrence of the keywords that appear in these research studies was carried out using the VOSviewer software, which is used to construct and visualise bibliographic networks [260]. These studies can show the critical points of research in this specific field, help to systematically understand its evolution, and provide future research directions.

At the same time, the different methodologies used in the selected studies have been studied, including objective measurements and subjective surveys. In addition, all the indices used for the assessment of thermal comfort have been compiled.

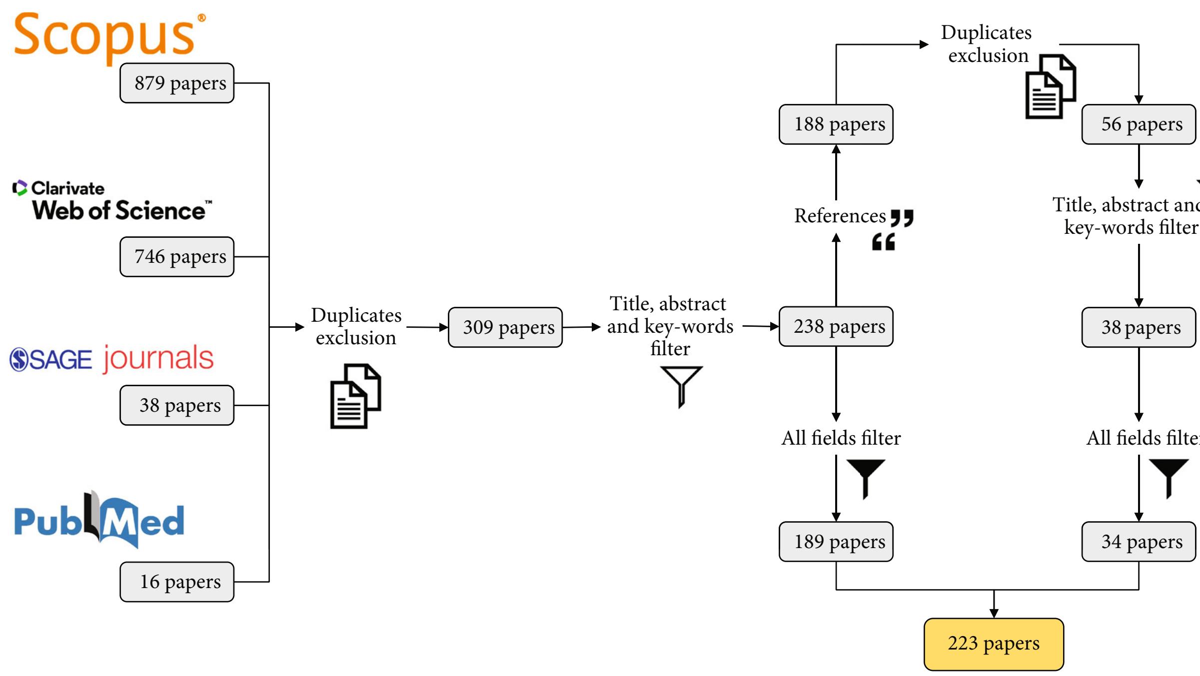


Figure 1: Literature search procedure.

On the other hand, a study was carried out on the compatibility of rational and adaptive thermal comfort approaches according to the academic level (primary, secondary, and university), the climatic zone according to the Köppen-Geiger classification (A, B, C, D, and E) and the season of the year (autumn, winter, spring, and summer) in which the different selected investigations were carried out. It should be noted that compatibility is defined as the coincidence between the actual thermal sensation, measured in terms of TSV, and the forecasts calculated by the two thermal comfort assessment methods used [28, 154]. The different neutral and comfort temperature ranges have also been evaluated according to the same classification.

Finally, the values calculated by the different authors for operating temperature (T_{op}) and average outdoor temperature (T_{out}), both parameters measured in °C, have been compiled to present the results in the adaptive thermal comfort graph proposed by the ASHRAE 55 standard [53]. This graph is based on the adaptive comfort equation developed by de Dear [261], which considers the evolution of outdoor temperatures as a factor that directly influences the thermal sensation of people. Thus, two ranges of comfort operating temperatures are defined for outdoor temperatures ranging from 10 to 33.5°C. For the first range, the limit operating temperatures result from adding ±3.5°C to the comfort temperatures, assuming a percentage of acceptability of 80% (proportion of people who would theoretically feel comfortable). This range is intended for typical applications. For the second range, the limiting operating temperatures result from adding ±2.5°C to the comfort temperatures, resulting in an acceptability percentage of 90%. This range is intended for situations where a more stringent level of thermal comfort would be desirable [21, 53]. Additionally, the correlation between TSV and PMV has been studied with T_{op} as a function of educational level, season, climate zone, and ventilation type, and the resulting equations for each category are presented.

3. Results and Discussion

This section presents the main results obtained from the bibliometric study and the critical review of the literature. In this way, the most relevant parameters of the 223 field studies on thermal comfort in educational buildings examined for this work are included in Table 2.

3.1. Characterization of Articles and Publication Trend. An exhaustive characterization of the articles selected for this review was carried out. Through thorough analysis, the trend of their publication has been evaluated, taking into account different parameters. This detailed and rigorous study allows us to place the evolution of thermal comfort in classrooms in a broader context and to understand the trends and patterns that have emerged in the scientific literature.

Figure 2 shows the yearly distribution of the selected articles. All papers are arranged according to the year in which the studies were conducted and the year in which they were finally published. In addition, the number of studies carried out in recent years is highlighted, particularly in the context of the COVID-19 pandemic. Of the 223 publications analysed, 24 (10.75%) belong to this period.

Firstly, an upward trend in scientific production over the last decade is evident, which has become more significant in the last five years. There is also a time lag between the dates when studies were carried out and when they were published

Table 2: Summary of reviewed papers.

Level	Authors	Year	Country	Climate	Op. mode	Season	Sample size	TC model	Temperature (°C) Neutral	Temperature (°C) Outdoor	Model compatibility A	Model compatibility R	Regression equation	Adaptive equation
P	Conceição and Lúcio [61]	2008	Portugal	Csa	MM	W	800	R	-	-	-	-	-	-
P	Theodosiou and Ordoumpozanis [62]	2008	Greece	Csa	MM	W MS	3716	O	-	-	-	-	-	-
P	Zeiler and Boxem [63]	2009	Netherlands	Cfb	MM	W Sp	174	R	24	-	-	U	-	-
P	Ter Mors et al. [64]	2011	Netherlands	Cfb	NV	All	79	R+A	-	24	L	U	-	-
P	Al-Rashidi et al. [36]	2012	Kuwait	Bwh	MM	Sp	-	O	-	28-41	-	-	-	-
P	Appah-Dankyi and Koranteng [65]	2012	Ghana	Aw	NV	W	116	A	-	31.70	-	U	-	-
P	Teli et al. [66]	2012	UK	Cfb	NV	Sp Su	1300	R+A	20.50	10.60-16.70	L	U	-	$T_c = 0.44T_{rm} + 15.70$
P	De Giuli et al. [4]	2012	Italy	Cfa	NV	Sp	614	A	-	15.30	-	U	-	-
P	Barrett et al. [67]	2013	UK	Cfb	MM	All	751	O	-	-	-	-	-	-
P	Teli et al. [68]	2013	UK	Cfb	FR	Sp	1314	R	20.50	10.60-16.70	H	U	$TSV = 0.27T_{op} - 5.55$	-
P	Haddad et al. [69]	2013	Iran	Bsh	NV	W MS	794	R	-	-	-	-	-	-
P	Turunen et al. [6]	2014	Finland	Dfb	MM	Sp Su	4248	O	-	-	-	-	-	-
P	Nematchoua et al. [70]	2014	Cameroon	Af Aw	NV	DS WS	1450	A	25 24.7	-	-	-	$TSV = 0.335T_a - 8.843$ $TSV = 0.407T_a - 9.855$	
P	De Giuli et al. [71]	2014	Italy	Cfa	MM	Sp	62	R	-	-	-	-	-	-
P	Teli et al. [72]	2014	UK	Cfb	NV	Su	560	A	-	10.60-16.70	H	-	-	-
P	Haddad et al. [73]	2014	Iran	Csa	NV	Sp	1605	R	22.80	-	-	O	$TSV = 0.23T_{op} - 5.24$	-
P	Huang et al. [74]	2014	Taiwan	Cfa	NV	Su MS	-	A	-	24	-	-	-	-
P	Trebilcock et al. [75]	2014	Chile	Csb	NV	W Su	2100	A	16.70 21.10	-	L	-	-	-
P	De Giuli et al. [76]	2014	Italy	Cfa	MM	W Sp	-	R+A	-	15.30	-	-	-	-
P	Dorizas et al. [77]	2015	Greece	Csa	NV	Sp	193	R	22.30	-	-	U	$TSV = 0.510PMV + 0.693$	-
P	Haddad et al. [78]	2016	Iran	Bsh	MM	All	1605	R+A	22.30	27.30	-	-	$TSV = 0.268T_{op} - 6.251$ $PMV = 0.225T_{op} - 5.339$	-
P	Huang and Hwang [79]	2016	Taiwan	Cfa	MM	MS	-	O	28	15-30	-	-	-	-
P	Trebilcock et al. [80]	2017	Chile	Csa	FR	W Sp	440	A	-	4-14.90 13-29.50	L	-	-	$T_c = 0.83T_{rm} + 7.11$
P	Teli et al. [81]	2017	UK	Cfb	NV	Sp Su	2784	A	22.60	15.40	L	-	-	$Tc = 0.26T_{rm} + 18.20$
P	Stazi et al. [82]	2017	Italy	Csa	MM	W Sp	-	R+A	-	-	H	O	-	-
P	Montazami et al. [83]	2017	UK	Cfb	MM	Su	662	A	22	27	-	-	$TSV = 0.2889T_a + 30.939$ $TSV = -0.2739T_a + 58.789$	-
P	Montazami et al. [84]	2017	UK	Cfb	NV	Su	662	A	22	27	-	-	-	-

Table 2: Continued.

Level	Authors	Year	Country	Climate	Op. mode	Season	Sample size	TC model	Temperature (°C) Neutral	Temperature (°C) Outdoor	Model compatibility A	Model compatibility R	Regression equation	Adaptive equation
P	Martínez-Molina et al. [85]	2017	Spain	Csa	NV	Au W	292	R	-	16	-	O	-	-
P	Bluyssen et al. [2]	2018	Netherlands	Cfb	MM	Sp	1145	O	-	13.20-30	-	-	-	-
P	Haddad et al. [86]	2019	Iran	Bsh	NV	All	811	A	22.30	27.30	-	-	$TSV = 0.27T_{op} - 6.25$	-
P	Branco et al. [87]	2019	Portugal	Cwb	MM	All	-	O	-	-	-	-	-	-
P	Toyinbo et al. [88]	2019	Nigeria	Aw	NV	DS WS	482	O	32	22-30	-	-	-	-
P	Zhang et al. [22]	2019	Netherlands	Cfb	-	Sp	1145	O	-	-	-	-	-	-
P	Zhang et al. [89]	2019	Netherlands	Cfb	-	Sp	1145	O	-	-	-	-	-	-
P	Simanic et al. [40]	2019	Sweden	Dfc	MM	All	-	O	-	-	-	-	-	-
P	Bluyssen et al. [90]	2019	Netherlands	Cfb	MM	Sp	335	O	-	-	-	-	-	-
P	Chen et al. [91]	2019	Taiwan	Cfa	NV	Su	-	O	-	-	-	-	-	$T_n = 0.62T_{out} + 12.10$
P	Ma et al. [92]	2020	China	Dwa	NV	W	141	R+A	18.05	5.90	L	U	$TSV = 0.291T_{op} - 5.249$ $PMV = 0.478T_{op} - 9.176$	-
P	Hamzah et al. [93]	2020	Indonesia	Am	NV	Sp	1111	R+A	25.50 30.20 29.40	30.40	C	O	$PMV = 0.37T_{op} - 9.37$ $TSV = 0.22T_{op} - 6.64$ $TCV = 0.20T_{op} - 5.91$	-
P	Korsavi et al. [94]	2020	UK	Cfb	MM	All	805	A	20.90 20.20	12.74	L	-	$TSV = 0.09T_{op} - 1.78$ (NV) $TSV = 0.14T_{op} - 2.80$ (HS)	-
P	Munonye [95]	2020	Nigeria	Aw	NV	DS WS	350	A	28.50 28.10	29.15	-	-	$TSV = 0.31T_{op} - 8.83$ $TSV = 0.21T_{op} - 5.91$	-
P	Munonye [96]	2020	Nigeria	Aw	NV	DS WS	330	R+A	28.10 28.80	29.60	H	O	$TSV = 0.24T_{op} - 6.90$ $TSV = 0.36T_{op} - 10.14$	-
P	Talarosha et al. [97]	2020	Indonesia	Am	NV	Sp	-	O	30.50 34.50	23.10- 34.30	-	-	-	-
P	Verma and Netam [98]	2020	India	Aw	NV	All	-	R	-	-	-	O	-	-
P	Abuelnuor et al. [99]	2021	Sudan	Bwh	MM	Su	-	R+A	-	34.60- 35.30	C (AC)	-	-	-
P	Guerrero et al. [100]	2021	Colombia	Cfb	NV	WS	-	A	-	-	-	-	-	-
P	**Gómez Melgar et al**. [101]	**2021**	**Spain**	**Csa**	**NV**	**W**	-	**O**	**19.37** **24**	-	-	-	-	-
P	**Alonso et al**. [45]	**2021**	**Spain**	**Csa**	**MM**	**W**	**50**	**R+A**	-	-	-	-	-	-
P	Pertiwi et al. [102]	2021	Indonesia	Am	NV	Sp	-	O	-	19-33	-	-	-	-
P	Aparicio-Ruiz et al. [103].	2021	Spain	Csa	MM	Su	67	R+A	-	22.50	-	-	$TSV = 0.19T_{op} - 4.07$ (FR) $PMV = 0.37T_{op} - 10.68$ (FR) $TSV = 0.19T_{op} - 4.49$ (AC) $PMV = 0.32T_{op} - 8.95$ (AC)	-
P	Mohamed et al. [104]	2021	Sudan	Bwh	MM	All	-	A	-	-	-	-	-	-
P	Munonye et al. [105]	2022	Nigeria	Aw	NV	All	330	A	31.60	23-37.40	L	-	$TSV = 0.29T_{op} - 8.33$	-

TABLE 2: Continued.

Level	Authors	Year	Country	Climate	Op. mode	Season	Sample size	TC model	Temperature (°C) Neutral	Temperature (°C) Outdoor	Model compatibility A	Model compatibility R	Regression equation	Adaptive equation
P	Lala et al. [106]	2022	India	Cwb	FR	W Su	5297	A	-	-	L	-	$MSV = 0.077T_a - 1.458$ $MSV = 0.113T_a - 1.903$ $MSV = 0.030T_a - 0.771$ $MSV = 0.039T_a + 0.983$ $MSV = 0.062T_a - 0.019$ $MSV = 0.114T_a - 1.898$	-
P	Aleixo and Curado [107]	2022	Portugal	Csb	NV	W	-	A	-	-	-	-	-	-
P	Suradhuhita et al. [108]	2022	Indonesia	Am	NV	DS	-	O	-	-	-	-	-	-
P	**Vignolo et al. [45]**	**2022**	**Uruguay**	**Cfa**	**NV**	**Sp**	**30**	**O**	-	**14.80-17.90**	-	-	-	-
P	Yao et al. [109]	2023	Malaysia	Af	NV	-	48	O	-	27.92-30.37	-	-	-	-
P	**Grygierek et al. [111]**	**2023**	**Poland**	**Cfb**	**NV**	**All**	**30**	**O**	-	-	-	-	-	-
S	Kwok [111]	1998	USA	Aw	MM	W Su	2181 1363	R+A	26.80 (NV) 27.40 (AC)	27.95	C	U	-	-
S	De Paula Xavier and Lamberts [112]	2000	Brazil	Cfa	NV	All	108	R	22.90	-	-	U	-	-
S	Wong and Khoo [113]	2003	Singapore	Af	NV	Su	493	R	28.80	-	-	O	$MSV = 0.53T_{op} - 15.43$	-
S	Kwok and Chun [114]	2003	Japan	Cfa	MM	Su	74	R+A	-	-	C	C	-	-
S	Wargocki and Wayon [115]	2007	Denmark	Cfb	NV	Su	470	O	20	16.60	-	-	-	-
S	Wargocki and Wayon [116]	2007	Denmark	Cfb	NV	Su	-	R	20	16.60	-	-	-	-
S	Al-Rashidi et al. [117]	2009	Kuwait	Bwh	AC	Au	336	R+A	-	-	L	O	-	-
S	Mumovic er al [118].	2009	UK	Cfb	MM	W	-	R	-	-	-	U	-	-
S	Puteh et al. [119]	2012	Malaysia	Af	NV	-	60	O	-	-	-	-	-	-
S	Wargocki and Wayon [14]	2013	Denmark	Cfb	AC	Su	-	O	20	-	-	-	-	-
S	d'Ambrosio Alfano et al. [120]	2013	Italy	Csa	NV	W Su	4000	R	20	-	-	O	TSV = 0.9PMV	-
S	Gao et al. [33]	2014	Denmark	Cfb	MM	W Sp	163	A	-	-1.30-30	-	-	-	-
S	Dias Pereira et al. [121]	2014	Portugal	Csa	NV	MS	45	R	25.20	28.10	-	O	-	-
S	Katafygiotou and Serghides [122]	2014	Cyprus	Csa	MM	All	-	R	20	-	-	-	-	-
S	Katafygiotou and Serghides [123]	2014	Cyprus	Csa Bsh	-	-	185	R	-	-	-	U, O	-	-
S	Dias Pereira et al. [124]	2015	Portugal	Csb	MM	W Sp	-	R	20	9.50-15	-	U, O	-	-
S	Barrett et al. [125]	2015	UK	Cfb	MM	All	3766	O	-	10.10	-	-	-	-
S	Almeida and Freitas [126]	2015	Portugal	Csb	MM	Sp	104	A	20-25	17.10	-	-	-	-
S	Liu et al. [127]	2016	China	Cwa	MM	Winter	763	R+A	15	-	C	U	$TSV = 0.1801T_{op} - 2.7174$ $PMV = 0.430T_{op} - 6.2446$	$aPMV = 0.224T_{op} - 3.3492$
S	Hamzah et al. [128]	2018	Indonesia	Am	AC	DS	1594	R	29 28.5	-	-	-	$PMV = 0.259T_{op} - 2.7174$ $TSV = 0.175T_{op} - 5.074$ $TCV = 0.204T_{op} - 5.814$	-

Table 2: Continued.

Level	Authors	Year	Country	Climate	Op. mode	Season	Sample size	TC model	Temperature (°C) Neutral	Temperature (°C) Outdoor	Model compatibility A	Model compatibility R	Regression equation	Adaptive equation
S	Jindal [129]	2019	India	Cwa	NV	W Su	1890	R+A	19.40 28.20	23.70	C	U, O	$TSV = 0.23T_{op} - 4.53$ $TSV = 0.17T_{op} - 4.95$	$T_n = 0.54T_{out} + 12.93$
S	Ali and Al-Hashlamun [130]	2019	Jordan	Bsh	NV	-	-	R+A	24	19.70	H	O	-	-
S	Monna et al. [131]	2019	Palestina	Csa	MM	All	-	O	-	-	-	-	-	-
S	Colinart et al. [132]	2019	France	Cfc	-	All	-	O	-	-	-	-	-	-
S	Calama-González et al. [133]	2019	Spain	Csa	MM	All	-	O	-	1.90-46.40	-	-	-	-
S	Shrestha and Rijal [134]	2019	Nepal	Cwa	NV	Au	818	A	27.20	25-33.90	C	-	$TSV = 0.17T_g - 0.60$ $TSV = 0.16T_g - 1.20$	$T_c = 0.472T_{out} + 13.80$
S	Chitaru et al. [39]	2019	Romania	Dfa	NV	W Su	26	R	-	-	-	-	-	-
S	Pistore et al. [38]	2020	Italy	Csa	MM	W Sp	-	O	-	-	-	-	-	-
S	Wang et al. [135]	2020	China	Cwa	AC	Su	-	R	-	27	-	-	$TSV(29^{\circ}C) = -1.47v_a + 1.34$ $PMV(29^{\circ}C) = -1.81v_a + 1.15$ $TSV(26^{\circ}C) = -1.50v_a - 0.09$ $PMV(26^{\circ}C) = -2.16v_a - 0.16$	-
S	Barbosa et al. [136]	2020	Portugal	Csa Csb	MM	W Sp	-	O	-	-	-	-	-	-
S	Heracleous and Michael [137]	2020	Cyprus	Csa	FR	W Su	606	A	-	24.78	L	-	-	-
S	Da Silva Jùnior et al. [138]	2020	Brazil	Aw	AC	Su	-	R	24-25	-	-	-	-	-
S	Al-Khatri et al. [139]	2020	Saudi Arabia and Oman	Bwh	AC	Su	657	R+A	24.30-26.10	21-35	C	O	-	-
S	Campano-Laborda et al. [140]	2020	Spain	Bsk Csa	MM	W Sp	977	O	-	8.30-18.50	-	-	-	-
S	Shrestha et al. [141]	2021	Nepal	Cwa	NV	Au	818	A	26.90	-	C	-	-	$T_c = 0.50T_{op} + 13.00$
S	**Zemitis et al. [48]**	**2021**	**Latvia**	**Dfb**	**NV**	**Su** **Au**	**346**	**O**	-	-	-	-	-	-
S	Heracleous et al. [142]	2021	Cyrpus	Csa	MM	All	-	O	-	19.90	-	-	-	-
S	Hamzah et al. [143]	2022	Indonesia	Am	NV	Su	1594	R+A	28.20-29.10	29.70	C	O	-	-
S	Nor Azli et al. [144]	2022	Malaysia	Af	NV	DS	46	O	-	28.10-29.90	-	-	-	-
S	Mustapha et al. [145]	2022	Nigeria	Aw	NV	DS WS	901	A	28.90	-	L	-	$TSV = 0.40T_{op} - 11.56$	-
S	Al-Khatri et al.	2022	Oman	Bwh	AC	W Su	1272	A	24.90	-	C	-	-	-
S	**Sekartaji et al. [147]**	**2023**	**Japan**	**Cfa**	**MM**	**W** **Su**	-	**O**	-	-	-	-	-	-
S	**Ding et al. [44]**	**2023**	**Netherlands**	**Cfb**	**MM**	**W** **Au**	-	**O**	-	**13.70-15.50**	-	-	-	-
P+S	Hwang et al. [147]	2009	Taiwan	Cfa	NV	W Au	1614	R+A	22.70-29.10	15-34	H	U	$MSV = 0.17T_{op} - 3.94$ $MSV = 0.01T_{op} - 0.30$ $MSV = 0.35T_{op} - 10.27$	-

Table 2: Continued.

Level	Authors	Year	Country	Climate	Op. mode	Season	Sample size	TC model	Temperature (°C) Neutral	Temperature (°C) Outdoor	Model compatibility A	Model compatibility R	Regression equation	Adaptive equation
P+S	Liang et al. [148]	2012	Taiwan	Cfa	Nv	All	1614	A	22.70-29.10	25	H	U	-	$T_n = 0.62T_{out} + 12.10$
P+S	De Dear et al. [149]	2015	Australia	Bwh	MM	Su	2850	R+A	22.50	21.67	L	U	$TSV = 0.12T_{op} - 2.78$	-
P+S	Wang et al. [150]	2017	China	Dwb Bwk	MM	All	1126	R+A	-	2.37	-	-	$MSV = 0.18T_{op} - 2.56$ $MSV = 0.13T_{op} - 1.74$ $MSV = 0.16T_{op} - 2.88$ $PMV = 0.40T_{op} - 5.95$ $PMV = 0.37T_{op} - 5.32$ $PMV = 0.41T_{op} - 6.07$	$aPMV = 0.22T_{op} - 3.22$ $aPMV = 0.21T_{op} - 3.03$ $aPMV = 0.21T_{op} - 2.98$
P+S	Kim and De Dear [30]	2018	Australia	Bwh	MM	Su	4866	A	24.40	21.30	L	-	$TSV = 0.17T_{diff} + 0.27$ $TSV = 0.15T_{diff} + 0.12$ $T_{diff} = T_{op} - T_n$	-
P+S	Jindal [151]	2018	India	Cwa	NV	Mon W	130	R+A	27.10	-	C	O	$TSV = 0.056T_{op} - 1.53$ $PMV = 0.19T_{op} - 4.58$	-
P+S	Campano et al. [152]	2019	Spain	Bsk Csa	NV	W MS	977	R+A	21.30	11.64	C	U	-	-
P+S	Boutet et al. [153]	2020	Argentina	Cfa	-	All	-	O	-	-	-	-	-	-
P+S	Jiang et al. [154]	2020	China	Cfa Bwk Bsk	NV	W	1206	R+A	13.90	1.98	H	U	$TSV = 0.14T_{op} - 1.95$ $PMV = 0.42T_{op} - 6.24$ $PMV = 0.37T_{op} - 4.94$ $PMV = 0.36T_{op} - 4.60$ $TSV = 0.18T_{op} - 2.56$ $PMV = 0.44T_{op} - 7.97$ $PMV = 0.44T_{op} - 6.73$ $PMV = 0.31T_{op} - 5.01$	$T_c = 0.27T_{out} + 13.80$
P+S	Rodríguez et al. [155]	2021	Colombia	Cfa	NV	MS	161	A	-	17.63	H	-	$TSV = 0.015T_{op} - 0.026$ $TSV = 0.217T_{op} - 4.206$	$T_c = 0.308T_{op} + 7.229$ $T_c = 0.094T_{op} + 2.041$
P+S	**Mori et al. [157]**	**2022**	**Japan**	**Dfb**	**MM**	**All**	-	**O**	-	-	-	-	-	-
P+S	**Babich et al. [158]**	**2023**	**Italy**	**Cfb**	**MM**	**W** **Sp**	-	**O**	-	-	-	-	-	-
U	Krüger and Zannin [158]	2004	Brazil	Cfa	NV	W Su	-	O	-	-	-	-	-	-
U	Hwang et al. [159]	2006	Taiwan	Cfa	MM	W	1294	R	24.70	-	-	U	$TSV = 0.1413ET^* - 3.762$ $PMV = 0.280ET^* - 7.717$	-
U	Zhang et al. [160]	2007	China	Cfa	NV	Sp	1273	R	21.50	-	-	O	$TSV = 0.0448T_{op} - 0.9628$ $PMV = 0.1162T_{op} - 2.8158$	-
U	Cheng et al. [161]	2008	Taiwan	Cfb	MM	MS Su	1219	R+A	25.40	-	L	U	$TSV = 0.338T_{op} - 8.40$ $TSV = 0.345T_{op} - 8.80$	-
U	Ogbonna and Harris [162]	2008	Nigeria	Aw	NV	Su	200	R+A	26.58	-	L	O	$TSV = 0.7082T_{op} - 18.823$ $PMV = 0.3318T_{op} - 8.3151$	-
U	Maki and Shukuya [163]	2008	Japan	Cfa	MM	Sp Su	1286	O	26	-	-	-	-	-

Table 2: Continued.

Level	Authors	Year	Country	Climate	Op. mode	Season	Sample size	TC model	Temperature (°C) Neutral	Temperature (°C) Outdoor	Model compatibility A	Model compatibility R	Regression equation	Adaptive equation
U	Hu et al. [164]	2008	China	Cfa	NV	W Su	593	R	22	-	-	-	$TSV = 0.13ET^{*} - 2.93$	-
U	Buratti and Ricciardi [165]	2009	Italy	Cfa	AC	W MS	959	R	23	14.30	-	C	$PMV = 0.1631T_{op} - 3.3086$	-
U	Corgnati et al. [166]	2009	Italy	Cfb	NV	W MS	230	R+A	-	20	L	O	-	-
U	Yao et al. [167]	2010	China	Cwa	NV	All	3621	R+A	22.80	-	H	O	$TSV = 0.17T_a - 3.06$	$T_c = 0.60T_{out} + 9.85$
U	Cao et al. [168]	2011	China	Dwa	MM	W Su	205	R	20.70-26.80		-	U	$TSV = 0.07ET^{*} - 1.70$	-
U	Jung et al. [169]	2011	South Korea	Dwa	NV	MS	962	R+A	22	15	H	O	-	$T_c = 0.422T_{out} + 16.90$
U	Liu et al. [170]	2011	Japan	Cfa	MM	W Su	65	O	-	-	-	-	-	-
U	Pellegrino et al. [171]	2012	India	Aw	NV	Su	100	R	30.90	34	-	O	$TSV = 0.6353T_{op} - 19.64$	-
U	Lee et al. [13]	2012	Hong Kong	Am	MM	-	312	R	23.60	-	-	-	-	-
U	Yang et al. [16]	2013	USA	Cfa	MM	W	627	O	-	-	-	-	-	-
U	Carvalho et al. [172]	2013	Portugal	Csa	NV	All	732	R+A	-	14.86	-	C	-	$T_c = 0.30T_{out} + 18.80$
U	Barbhuiya and Barbhuiya [7]	2013	UK	Cfb	MM	W Sp	-	O	-	7-22	-	-	-	-
U	Choi et al. [32]	2014	USA	Cfa	AC	-	631	O	-	-	-	-	-	-
U	Wang et al. [173]	2014	China	Dwb	NV	W Sp	200	R	22.70	16.55	-	-	$TSV = 0.24T_{op} - 5.43$	-
U	Baruah et al. [174]	2014	India	Cwa	NV	W Su	228	R	-	-	-	-	-	-
U	Tariq et al. [175]	2014	Bangladesh	Aw	NV	Su Mon	100	R	30.20	-	-	-	$TSV = 0.331T_a + 30.210$	-
U	Mishra and Ramgopal [5]	2014	India	Aw	NV	Sp	121	A	26.50	-	-	-	-	-
U	Mishra and Ramgopal [176]	2015	India	Aw	NV	W Sp	121	R+A	26.50	14.50	C	C	$TSV = 0.184T_{op} - 4.866$ $PMV = 0.180T_{op} - 3.570$	$T_c = 0.53T_{op} + 15.23$
U	Dhaka et al. [177]	2015	India	Bsh	NV	All	1811	R+A	27.21	29.21	H	O	$TSV = 0.169T_a - 4.598$ $PMV = 0.320T_a - 8.670$ $PMV = 0.150T_a + 4.140$	$T_c = 0.750T_{op} + 5.370$
U	Serghides et al. [178]	2015	Cyprus	Csa	MM	W Su	70	R+A	21-22 21-33	15.20 29.10	-	-	-	-
U	Mishra and Ramgopal [179]	2015	India	Aw	MM	Au Mon	444	A	-	-	C	-	-	$T_c = 0.14T_{op} - 3.72$
U	Mishra and Ramgopal [180]	2016	India	Aw	NV	All	67	A	29	23.50	C	-	$TSV = 0.22T_{op} - 6.37$	-
U	Vittal and Gnanasambandam [181]	2016	India	Aw	NV	W	176	R+A	29	-	L	C	$PMV = 0.256T_{op} - 6.081$ $TSV = 0.602T_{op} - 17.491$	-
U	Nico et al. [182]	2016	Italy	Csa	NV	W	126	R+A	22.20-22.60	14.05	C	C	-	-
U	Shaari et al. [183]	2016	Malaysia	Af	AC	DS WS	189	R+A	25	-	C	U	$PMV = 0.250T_{op} - 6.025$ $TSV = 0.497T_{op} - 13.706$	-

Table 2: Continued.

Level	Authors	Year	Country	Climate	Op. mode	Season	Sample size	TC model	Temperature (°C)		Model compatibility		Regression equation	Adaptive equation
									Neutral	Outdoor	A	R		
U	Thapa et al. [184]	2016	India	Cwa	NV	All	356	R+A	-	-	C	U, O	$TSV = 0.091T_g - 2.355$ $PMV = 0.204T_g - 4.551$	$T_c = 0.67T_{rm} + 9.094$ $T_n = 0.81T_g + 4.710$
U	Wang et al. [185]	201	China	Dwb	NV	W MS	30	R+A	18	-	H	-	$TSV = 0.16T_a - 2.97$	-
U	Zaki et al. [186]	2017	Malaysia Japan	Af Cfa	MM	Su	1428	R+A	26.50 26.30	28.98	C	-	$TSV = 0.332T_{op} - 8.80$ $TSV = 0.426T_{op} - 11.20$	-
U	Mishra et al. [187]	2017	Netherlands	Cfb	AC	Sp	384	A	-	5.90	-	-	-	-
U	Castilla et al. [188]	2017	Spain	Csa	-	-	918	O	-	-	-	-	-	-
U	Singh et al. [29]	2018	India	Bwh	NV	Sp Su	900	A	26.50	34.93	L	-	$TSV = 0.19T_a - 5.04$	$T_c = 0.49T_{rm} + 13.80$
U	Fang et al. [189]	2018	Hong Kong	Am	AC	Su	946	R+A	24.14	-	C	U	$PMV = 0.371T_{op} - 10.64$ $TSV = 0.324T_{op} - 8.30$	-
U	Kumar et al. [190]	2018	India	Aw	NV	Sp Su	900	R+A	26.50	25.20-41.20	-	-	$TSV = 0.19T_a - 5.04$	
U	López-Pérez et al. [191]	2019	Mexico	Aw	MM	Sp	496	A	26.40-25.60	24.30	H	-	$TSV = 0.405T_{op} - 10.64$ $TSV = 0.324T_{op} - 8.30$	$T_c = 0.13T_{rm} + 22.70$ $T_c = 0.32T_{rm} + 18.45$
U	Bajc et al. [31]	2019	Serbia	Cfa	MM	W	203	R	-	-	-	-	-	-
U	Aghniaey et al. [192]	2019	USA	Cfa	AC	Su	-	R+A	-	-	-	-	-	-
U	Liu et al. [193]	2019	China	Cfa	NV	Au	992	A	20.60	-	H	-	$TSV = 0.40T_{op} - 8.42$	$aPMV = 0.23T_{op} - 5.37$
U	Costa et al. [194]	2019	Brazil	Aw	MM	Su	178	O	-	28.40	-	-	-	-
U	Fabozzi et al. [195]	2019	Italy	Csa	MM	Su	985	R+A	-	-	-	-	-	-
U	Hamzah et al. [196]	2019	Indonesia	Am	AC	Sp	175	O	27.40	-	-	-	$TSV = 0.613T_a - 19.769$ $TCV = 0.412T_a - 11.201$	-
U	Shen et al. [197]	2019	China	Cwa	NV	W Su	587	R	-	8.30-28.80	-	-	-	-
U	Ranjbar [198]	2019	Turkey	Csa	MM	W Su	-	O	-	2.80-29.90	-	-	-	-
U	Lawrence et al. [199]	2019	UK	Cfb	MM	W Su	505	R	21.80	-	-	-	-	-
U	Heracleous and Michael [200]	2019	Cyprus	Bsh	NV	W	-	O	-	-	-	-	-	-
U	Huang et al. [201]	2019	China	Dwa	AC	Sp	-	O	-	-	-	-	-	-
U	Jing et al. [202]	2019	China	Cwa	HS	W	200	R	-	-5.90-6.80	-	O	$TSV = 0.1481T_{op} - 3.8294$ $PMV = 0.2234T_{op} - 4.9764$	-
U	Koranteng et al. [203]	2019	Ghana	Aw	NV	Sp Su	214	A	-	26.20-29	-	-	-	-
U	Li et al. [204]	2019	China	Cwa	AC	Su	25	O	-	-	-	-	-	-
U	Zhaosong et al. [205]	2019	Taiwan	Cfa	MM	Sp	257	R	-	-	-	-	-	-
U	Valladares et al. [206]	2019	Taiwan	Cfa	AC	Su	-	R	-	22.90-27.67	-	-	-	-
U	Liu et al. [207]	2019	China	Cwa	NV	W	178	R	20.27	13.21	-	-	$AMV = 0.2312T_a - 4.6869$ $PMV = 0.2532T_a - 5.7608$	-
U	Liu et al. [208]	2020	China	Dsd	MM	W Au	900	R+A	-	-	-	-	$MSV = 0.406T_{op} - 8.457$ $MSV = 0.208T_{op} - 4.839$	-

Table 2: Continued.

Level	Authors	Year	Country	Climate	Op. mode	Season	Sample size	TC model	Temperature (°C) Neutral	Temperature (°C) Outdoor	Model compatibility A	Model compatibility R	Regression equation	Adaptive equation
U	Jowkar et al. [209]	2020	UK	Cfb	FR	Au	3000	A	23	9.59	L	-	$MSV = 0.29T_{op} - 1.90$ $MSV = 0.28T_{op} - 1.80$	-
U	Talukdar et al. [210]	2020	Bangladesh	Aw	NV	Su	579	A	30.50	-	C	-	$TSV = 0.14T_{op} - 2.7084$	$Tc = 0.28T_{rm} + 16.10$
U	Jowkar et al. [211]	2020	UK	Cfb	MM	W Sp	3516	A	22-23.20	-	-	-	-	-
U	Jowkar et al. [212]	2020	UK	Cfb	MM	W MS	3512	O	22.30- 22.70	5.80-11.20	-	-	$TSV = 0.30T_{op} - 6.80$ $TSV = 0.30T_{op} - 6.50$ $TSV = 0.28T_{op} - 6.20$	-
U	Liu et al. [213]	2020	China	Bwk	NV	MS	992	A	20.60- 23.20	23.10- 25.90	-	-	$MSV = 0.41T_{op} - 8.42$ $MSV = 0.34T_{op} - 7.89$	-
U	Papadopoulos et al. [214]	2020	Greece	Csa	NV	W	198	R	-	-	-	U	$PMV = 0.237AMV - 0.210$	-
U	Kumar et al. [215]	2020	India	Cwa	NV	W Au	615	A	25.90	18.90	H	-	$TSV = 0.11T_g - 2.85$	$T_c = 0.38T_{rm} + 16.10$
U	Buonocuore et al. [216]	2020	Brazil	Aw	MM	All	2680	A	23-29	-	H	-	-	-
U	Balbis-Morejón et al. [217]	2020	Colombia	Af	AC	-	584	R+A	23	30	L	U	$TSV = 0.9248T_{op} - 11.368$ $PMV = 0.3698T_{op} - 9.6994$ $PMV = 0.3440T_{op} - 8.9036$	-
U	Zhang et al. [218]	2020	China	Cwa	-	-	-	R	-	-	-	-	-	-
U	Subhashini et al. [219]	2021	India	Aw	MM	All	668	A	-	18-41	L	C	$AMV = 0.51T_{op} - 11.96$ $AMV = 0.27T_{op} - 6.65$	$T_c = 0.28T_{out} + 17.90$
U	Guevara et al. [220]	2021	Ecuador	Cfb Aw Af	MM	Su	429	R+A	21.80 26.30 26.80	23.10	L	U	$PMV = 0.22T_{op} - 5.22$ $PMV = 0.35T_{op} - 8.99$ $PMV = 0.31T_{op} - 7.66$ $TSV = 0.29T_{op} - 6.40$ $TSV = 0.37T_{op} - 9.76$ $TSV = 0.49T_{op} - 12.97$	-
U	Nguyen [221]	2021	Vietnam	Aw	AC	Su	169	R+A	28.20	-	H	U	-	-
U	Wang et al. [222]	2021	China	Dwa	MM	All	1973	R+A	20.20- 22.40	19.58	C	U	$PMV = 0.407T_{op} - 9.990$ $PMV = 0.350T_{op} - 9.085$ $PMV = 0.206T_{op} - 4.858$ $PMV = 0.157T_{op} - 3.434$ $TSV = 0.076T_{op} - 1.198$ $TSV = 0.289T_{op} - 7.569$ $TSV = 0.004T_{op} - 0.345$ $TSV = 0.268T_{op} - 6.005$	-
U	Attaianese et al. [223]	2021	Italy	Csa	MM	All	562	R	-	-	-	-	-	-
U	Nakagawa and Nakaya [224]	2021	Japan	Cfa	MM	W Au	1284	O	-	9.60	-	-	-	-
U	**Ulpiani et al. [226]**	**2021**	**Australia**	**Cfa**	**NV**	**All**	-	**O**	-	-	-	-	-	-
U	**Mamica et al. [227]**	**2021**	**Poland**	**Cfb**	**NV**	**All**	**906**	**O**	-	-	-	-	-	-
U	Liu et al. [227]	2021	China	Cfa	NV	Sp	60	R+A	26.50	-	-	-	$TSV = 0.1347T_a - 2.9825$ $PMV = 0.2165T_a - 5.0759$	-

Table 2: Continued.

Level	Authors	Year	Country	Climate	Op. mode	Season	Sample size	TC model	Temperature (°C)		Model compatibility		Regression equation	Adaptive equation
									Neutral	Outdoor	A	R		
U	Su et al. [228]	2021	China	Dwa	HS	W	641	R+A	21.70	-	-	-	$MSV = 0.325T_{op} - 7.043$	-
U	Dębska and Krakowiak [229]	2021	Poland	Cfb	-	-	9	R	-	-	-	-	-	-
U	**Anastasi et al. [231]**	**2021**	**Italy**	**Csa**	**MM**	-	**707**	**O**	-	-	-	-	-	-
U	Hu et al. [231]	2022	China	Cfa	NV	W	2110	O	-	5.80-14.50	-	-	-	-
U	**Ovando-Chacon et al. [233]**	**2022**	**Mexico**	**Aw**	**MM**	**All**	**30**	**O**	-	-	-	-	-	-
U	Gangrade and Sharma [233]	2022	India	Aw	NV	W WS	2674	R+A	27.70	19.90-31.80	L	O	$TSV = 0.19T_a - 5.272$	$T_c = 0.31T_{out} + 17.79$
U	Zhang et al. [234]	2022	China	Dwa	MM	W	133	R+A	22.60	4.70	L	O	$MSV = 0.3418T_a - 7.3123$ $PMV = 0.3308T_a - 7.2038$	-
U	Abdallah et al. [235]	2022	Egypt	Bwh	NV	Sp Su	116	O	-	-	-	-	-	-
U	Shi et al. [236]	2022	China	Dwa	HS	W Au	89	R+A	18.50	-5-17	C	C	$TSV = 0.122T_{op} - 2.817$ $PMV = 0.121T_{op} - 3.023$	-
U	**Miranda et al. [42]**	**2022**	**Spain**	**Csa**	**MM**	**W**	-	**R**	**18.12**	-	-	-	-	-
U	**Aguilar et al. [43]**	**2022**	**Spain**	**Csa**	**MM**	**All**	**491**	**O**	-	-	-	-	$\mathbf{TSV = 0.16T_a - 3.66}$	-
U	**Sekartaji et al. [238]**	**2022**	**Japan**	**Cfa**	**MV**	**Su** **Sp**	**106**	**O**	-	**20-31.50**	-	-	-	-
U	Krawczyk and Zender [238]	2022	Poland	Cfb	MM	Sp	75	R	-	22-27	-	-	-	-
U	**Rodríguez-Vidal et al. [240]**	**2022**	**Spain**	**Cfb**	**NV**	**All**	-	**O**	-	-	-	-	-	-
U	**Aguilar et al. [241]**	**2022**	**Spain**	**Csa**	**NV**	**W** **Au**	**989**	**R**	**23.80**	**13.10**	-	-	$\mathbf{TSV = 0.20T_{op} - 4.99}$	-
U	**Aguilar et al. [242]**	**2022**	**Spain**	**Csa**	**MM**	**W**	**908**	**A**	-	-	-	-	$\mathbf{TSV = 0.25T_{op} - 5.55}$ $\mathbf{TSV = 0.26T_{op} - 6.20}$	-
U	**Alegría-Sala et al. [243]**	**2022**	**Spain**	**Csa**	**MM**	**All**	-	**O**	-	-	-	-	-	-
U	Krawczyk et al. [243]	2022	Poland	Cfb	NV	All	205	O	-	-	-	-	-	-
U	Dodón et al. [244]	2022	Panama	Am	MM	W	182	O	-	-	-	-	-	-
U	Jia et al. [245]	2022	Hong Kong	Am	-	-	655	O	-	-	-	-	-	-
U	Su et al. [246]	2022	New Zelend	Cfb	NV	All	-	O	-	-	-	-	-	-
U	Izzati et al. [247]	2023	Malaysia	Af	AC	All	252	A	24.90	27.50-28	-	-	-	$T_c = 0.42T_{rm} + 12.30$
U	Shrestha and Rijal [248]	2023	Nepal	Cwb	NV	Sp	246	O	26.90	-	-	-	-	-
U	**Sekartaji et al. [250]**	**2023**	**Japan**	**Cfa**	**AC**	**Su**	**1141**	**R**	**28**	-	-	-	$\mathbf{TSV = 0.3522T_a - 9.6118}$	
U	Alghamdi et al. [250]	2023	Australia	Cfa	MM	W Su	154	A	27.50	-	-	C	-	-
U	**Rus et al. [252]**	**2023**	**Romania**	**Dfb**	**MM**	**W**	**177**	**R**	-	**0-4**	-	**U**	$\mathbf{PMV = 0.34T_{op} - 8.381}$ $\mathbf{TSV = 0.569T_{op} + 13.831}$ $\mathbf{PMV = 0.185T_{op} - 4.633}$ $\mathbf{TSV = 0.711T_{op} + 16.722}$	-
U	Ege Çeter et al. [252]	2023	Turkey	Csb	MM	All	1159	R+A	-	-	C	O	-	-
U	Bueno et al. [253]	2023	Brazil	Cfb	NV	Au	519	O	-	-	-	-	-	-
U	Vivek et al. [254]	2023	India	Aw	AC	Su	-	O	-	-	-	-	-	-
S+U	Corgnati et al. [255]	2007	Italy	Cfa	NV	W	440	R	-	-	-	-	-	-

Table 2: Continued.

Level	Authors	Year	Country	Climate	Op. mode	Season	Sample size	TC model	Temperature (°C)		Model compatibility		Regression equation	Adaptive equation
									Neutral	Outdoor	A	R		
S+U	**Rodríguez et al. [47]**	**2022**	**Spain**	**Csa**	**MM**	**All**	-	**O**	-	-	-	-	-	-
P+S +U	Almeida et al. [256]	2016	Portugal	Csb	FR	Sp	487	R+A	-	-	-	-	-	-
P+S +U	**Torriani et al. [258]**	**2023**	**Italy**	**Csa**	**MM**	**W**	**859**	**R+A**	**21.70-22.20**	**11.50**	**C**	**U**	$\mathbf{PMV = 0.26}T_{op}\mathbf{ - 6.50}$ $\mathbf{TSV = 0.25}T_{op}\mathbf{ - 5.58}$ $\mathbf{TSV = 0.32}T_{op}\mathbf{ - 7.12}$	-

(*) Information in bold corresponds to studies conducted under pandemic conditions by COVID-19. P: primary education level; S: secondary education level; U: university level; NV: natural ventilation; AC: air conditioning; HS: heating system; FR: free running; MM: mixed mode; MV: mechanical ventilation; all: entire full year; W: winter; Au: autumn; Sp: spring; Su: summer; MS: mid-season; DS: dry season; WS: wet season; Mon: monsoon; R: Fanger's rational thermal comfort model; A: adaptive thermal comfort model; H: high adaptability; L: low adaptability; C: compatibility; U: underestimation; O: overestimation; TSV: thermal sensation vote; PMV: predicted mean vote; MSV: mean sensation vote; TCV: thermal comfort vote; AMV: actual mean vote; T_{op}: operative temperature; T_c: comfort temperature; T_a: air temperature; T_{rm}: mean radiant temperature; T_g: globe temperature; T_n: neutral temperature and ET*: effective temperature.

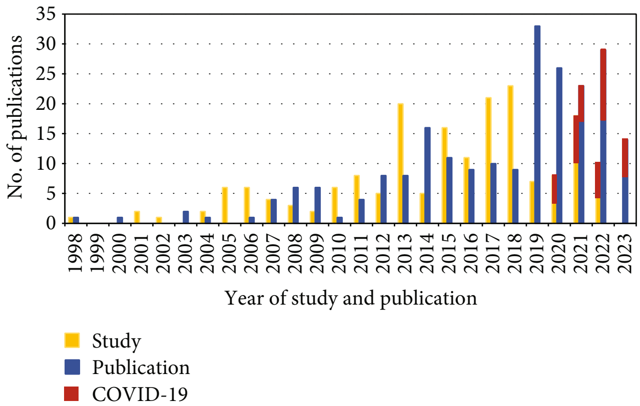


FIGURE 2: Articles' annual distribution.

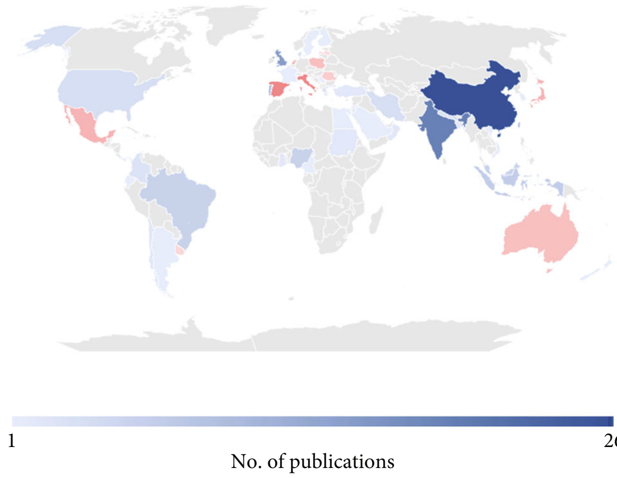


FIGURE 3: Distribution of publications by country.

in journals and conference proceedings, with a gap of up to eight years [14]. The year 2019 marked the peak in terms of published papers, while 2017 and 2018 were the years with the highest number of studies conducted. According to those observed, many of the studies carried out and published since 2020 have focused on assessing how ventilation protocols established in educational environments to curb COVID-19 infections have influenced thermal comfort (30% of the total for this period). Finally, and even though not all publications have been collected for the year 2023 due to the revision date of the articles included in this work, it is expected that the number of research studies will be maintained or may even increase, due to the interest that the relationship between the energy consumption of buildings and the thermal comfort of the occupants also arouses, especially within the current context of savings due to climate change and the crisis in energy prices and supplies.

Figure 3 shows the countries where research on thermal comfort in educational buildings has been carried out over the last 25 years. Lighter shades can be seen for those countries that have published fewer articles, starting from a single publication, and darker shades for those regions where more research has been carried out, up to a maximum of 26 publications. Thus, the countries with the highest scientific production in this field are China (26), India (19), the United Kingdom, Italy, and Spain (15). In the case of countries such as China, India, Iran, and Taiwan, more field studies are carried out due to the need to analyse thermal comfort in regions with extreme climates where air conditioning is essential. On the other hand, in countries such as Spain, Italy, and Portugal, where temperate climates prevail over most of the territory, studies are mainly focused on the evaluation of thermal comfort conditions using natural ventilation. These studies mainly reflect the perception of thermal comfort by classroom occupants depending on the characteristics of the buildings and the seasons of the year.

At the same time, countries, where thermal comfort studies have been carried out in the context of the COVID-19 pandemic, are highlighted in red. As can be seen, most of the studies were carried out in Spain and Italy. Also, the high cumulative incidence recorded during this period meant that in these two countries, natural ventilation measures, preferably cross ventilation, were mandatory in educational buildings whenever possible due to their characteristics [262, 263]. Looking at the rest of the research in other countries, most of the research where natural ventilation protocols existed was done in temperate climates. This might give an idea that such measures might not be the most appropriate in climatic zones with more extreme characteristics [237].

To follow, Figure 4 shows the keyword cooccurrence map, where each node with its respective label represents a keyword. The size of each node reflects the number of occurrences it had in total, i.e., the larger it is, the higher its frequency, while the thickness of the lines is proportional to the closeness of keyword connections. For this work, a minimum of 5 occurrences per keyword were selected, to choose the ones that carried the most weight. The centrality indicates the most influential nodes, as they are the ones with the highest number of cooccurrences with another thermal within the network. The colour of each node represents the grouping of terms offered by VOSviewer, called a cluster [260]. Thus, a total of six distinct clusters can be seen, with a significant correlation between the keywords in each group.

(i) *Cluster 1 (Green).* The main area of research is to be found in the term "thermal comfort," which appears within this cluster and is the largest and most central node on the map. This term is directly related to 23 of the 29 keywords collected. Also included are terms related to the subjective preferences that occupants have for the indoor thermal environment.

(ii) *Cluster 2 (Red).* In this cluster, terms relating to the locations where the selected studies were conducted, i.e., classrooms and educational buildings at different levels, have been included.

(iii) *Cluster 3 (Dark Blue).* It encompassed five keywords referring to indoor air quality. This cluster groups

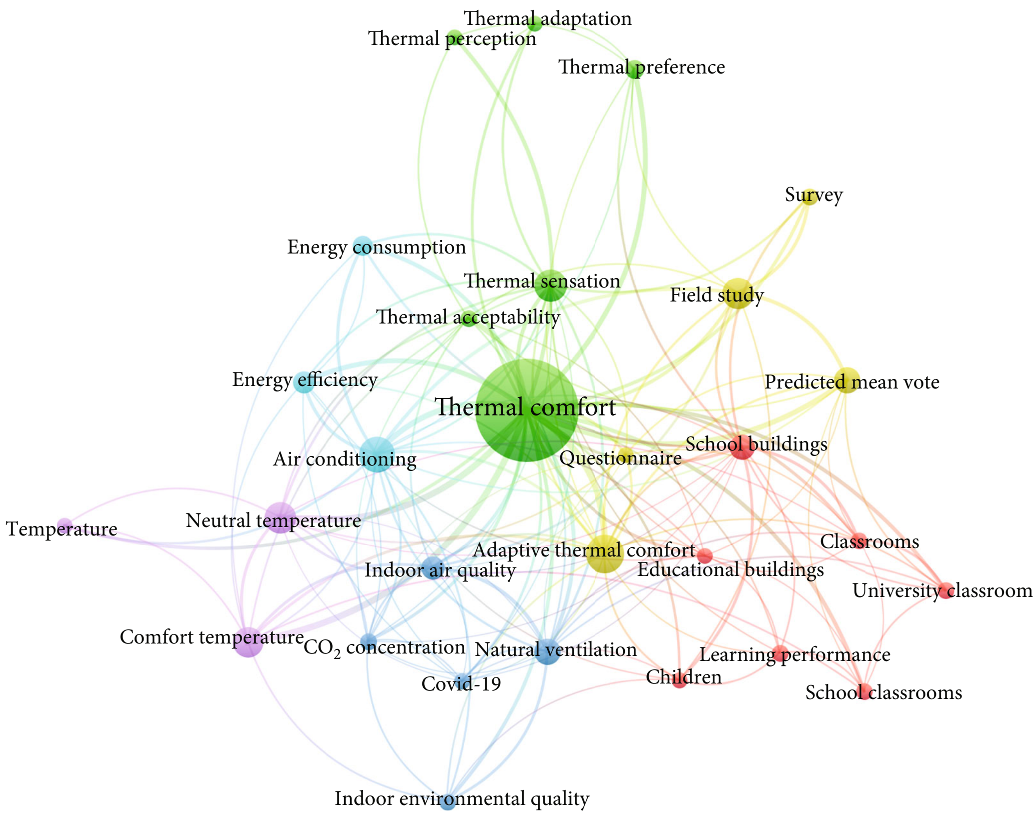


Figure 4: Cooccurrence of papers' keywords.

together terms such as natural ventilation, CO_2 concentration, and COVID-19. This shows the importance of these parameters for thermal comfort, especially in recent years.

(iv) *Cluster 4 (Yellow).* Terms related to the thermal comfort assessment methods used. The keyword "adaptive thermal comfort" has the highest frequency and is related to one or more terms from the other clusters.

(v) *Cluster 5 (Purple).* Keywords linked to temperature as the main parameter influencing thermal comfort are included.

(vi) *Cluster 6 (Light Blue).* This cluster refers to concepts related to energy efficiency and consumption, associated in most of the works reviewed with the use of air conditioning systems as a tool for achieving correct thermal comfort conditions.

Finally, to assess the impact of research on thermal comfort in educational centres, an analysis of the journals, their fields, and impact factors, as well as the number of citations of the different studies, was carried out. Among the 223 papers selected, a total of 76 international journals and conference proceedings were identified, mainly covering research areas focused on engineering and architecture, energy, and sustainability. However, it is also possible to find, to a lesser extent, publications focusing on the assessment of thermal comfort in human health. Almost half of the articles were published in journals in the first quartile of their field in the research year, while 25% were published equally in Q2 and Q3 journals. Of all the papers reviewed, 23 have no citations to date, while 47% have at least 20 citations. Of the total, 13% of the studies have 100 or more citations. The most cited paper has 265 citations. These data show that this research topic has attracted a great deal of interest from the scientific community in assessing the relationship between an adequate indoor environment in educational classrooms and students' ability to learn and solve problems [264].

3.2. Review Results of Field Studies. The results of the reviewed studies are presented in the following sections: number of participants involved, thermal indices used, climatic zone, season, mode of operation, and level of education. In addition, a compatibility study was carried out between the different thermal comfort approaches, taking into account the parameters mentioned above. Finally, the adaptive thermal comfort equations and the regression equations of the TSV and PMV indices were evaluated.

3.2.1. Number of Participants Involved. The papers selected for this literature review included 9 to 5297 participants for the development of classroom thermal comfort field studies [106, 229]. The average total participation was 840 students. The average number of participants in the studies carried out during COVID-19 was significantly lower, at 263. This

Table 3: Number of participants in the studies selected.

No. of participants range	No. of publications
<100	22
100-500	58
500-1,000	48
1,000-2,500	29
2,500-5,000	4
>5,000	1

reflects the capacity measures in place to prevent the spread of the virus [262]. As shown in Table 3, more than half of the studies had a participation of 500 people or more, so in most cases, there was large participation, which is a prerequisite for more accurate results. Although, in general, occupancy rates in secondary and university classrooms tend to be higher than in primary school [265], lower participation was observed at these educational levels. In cases where the experiments had a high number of participants, this was mainly because the studies were conducted in different seasons of the year or under different ventilation and air-conditioning conditions.

It should be noted that most of the studies conducted investigated the two genders separately. Although in most cases no significant difference was shown [186], it became clear that this issue is important in countries with religious dress restrictions for women [117, 204, 212, 231, 252].

3.2.2. Thermal Indices Used in Field Surveys. This section summarises the thermal indices applied in the different publications reviewed, following the study conducted by de Freitas and Grigorieva [266], as shown in Table 4. Air temperature (T_a) and relative humidity (RH) were the two most frequently used indices, with a total of 198 and 172 publications, respectively. These parameters are two of the four environmental factors, together with air velocity and mean radiant temperature, whose measurement is necessary to carry out any objective study of thermal comfort [267–270]. In most of the works that have studied the ventilation measures implemented during the COVID-19 pandemic, the aforementioned indices have been used exclusively to establish some relationship with the existing thermal comfort conditions [43, 44, 47, 146, 225, 230, 237, 239].

It can also be seen how the TSV (for some authors AMV) and PMV indices were the next most used, appearing in 57 and 44% of the cases. The PMV represents the mean vote determined from the mean of the TSV values [271]. However, several studies have analysed the discrepancy between the two terms in favour of the latter, especially in cases where thermal comfort in naturally ventilated classrooms has been analysed [167, 169, 177, 207, 214]. Therefore, some authors claimed that updates to the PMV model should be made by applying expectation factors and adaptive coefficients, proposing the ePMV, aPMV, and cPMV indices, which take into account the difference in expectations between nonacclimatised individuals and behavioural, physiological, and psychological adaptations [272–274].

Table 4: Frequency of thermal indices applied in the reviewed studies.

Indices	No. of publications	No. of publications in COVID-19 period
T_a	198	22
RH	172	19
TSV	127	7
PMV	98	7
TPV	87	2
T_{op}	69	4
PPD	68	5
TAV	49	1
TCV	24	1
PD	20	1
HSV	18	1
AMV	17	0
OC	16	0
MSV	12	0
APD	12	0
aPMV	7	0
ET*	6	0
DISC	4	0
SET*	3	0
ePMV	2	0
HIS	2	0
TIP	2	1
TsaV	2	1
cPMV	1	0
HPV	1	0

Finally, the TPV, TAV, and TCV indices are used in numerous investigations and are included in some of the thermal comfort evaluation surveys, especially in those carried out by university students because they can respond more accurately to the nuances of these questions [159, 164, 175, 186, 191, 216, 238, 253, 257]. The same is true for HSV and HPV where the effect of humidity is analysed independently [187, 210, 212, 215, 229, 235, 247].

3.2.3. Climatic Zone, Seasons, and Operation Modes. The Köppen-Geiger climate classification has been used to group studies of thermal comfort in classrooms. This classification identifies five main climate types, subdivided into a total of 37 classes, with a series of letters indicating the behaviour of temperature and precipitation that characterises each climate [275]. Thus, Figure 5 shows the number of studies collected for each climate zone, highlighting the proportion of work carried out in the context of establishing COVID-19 prevention measures.

The data show that most studies (60.68%) were carried out in group C of this classification, which corresponds to temperate climates. It can also be seen that more than 83% of the studies carried out during the pandemic period by

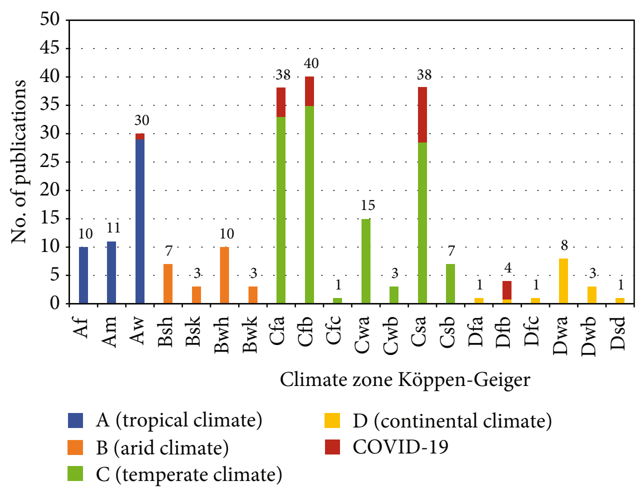


Figure 5: Number of studies per climatic zone.

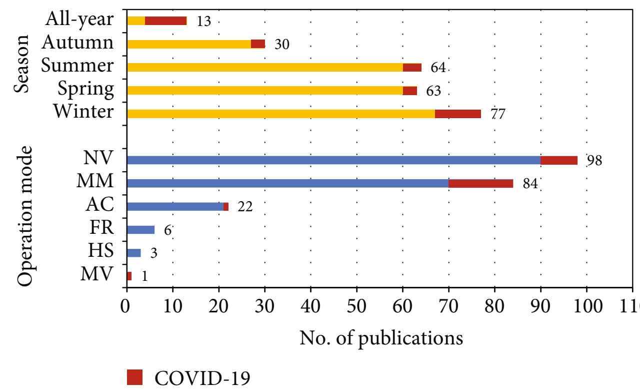
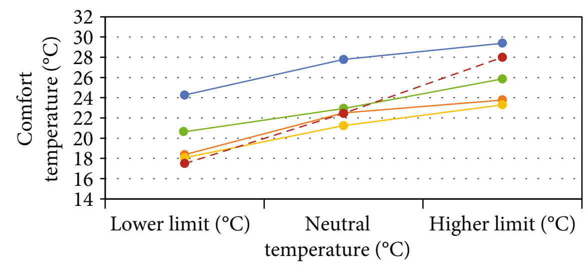


Figure 6: Publication number according to season and operation mode.



	Lower limit (°C)	Neutral temperature (°C)	Higher limit (°C)
A	24.26	27.78	29.39
B	18.37	22.49	23.78
C	20.65	22.93	25.86
D	18.07	21.24	23.3
COVID-19	17.5	22.45	28

Figure 7: Lower and upper limits and mean neutral comfort temperature for different climate zones.

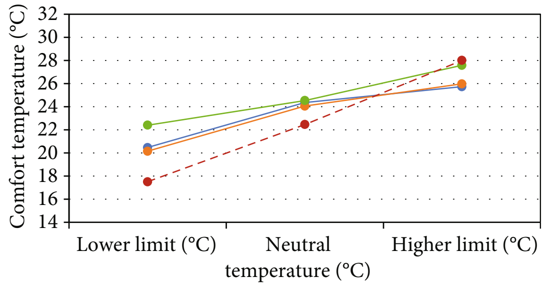
COVID-19 were in this climate zone. In these cases, as indicated above, the various strategies to prevent the spread of SARS-CoV-2 coronavirus infection were mainly aimed at promoting natural ventilation, whereas in more extreme climates, such measures could not be implemented. Some of the countries with studies on thermal comfort in educational buildings included in this review were China, Spain, Italy, the United Kingdom, Portugal, Taiwan, the Netherlands, Japan, Cyprus, Denmark, Poland, and India. Group A studies, corresponding to more tropical climates, were the second most common (21.79%) and included work carried out in India, Indonesia, Malaysia, and Nigeria, among others. This is followed by studies carried out in climate zone B (9.83%), i.e., in climates considered to be arid. Research in this group was mainly carried out in Iran, China, Australia, Kuwait, and Oman. On the other hand, 18 papers (7.69%) were found in group D, the continental climates, almost all of which were carried out in China. Finally, no such studies were found for group E, the polar and alpine climates.

Figure 6 shows the distribution of the investigations according to the seasons of the year and the mode of operation (ventilation and air-conditioning system). As can be seen, the selected studies were mostly conducted in winter and classrooms with only natural ventilation (NV), closely followed by rooms where the mode of operation was mixed (MM), considered as the joint use of two or more ventilation or air-conditioning systems [276]. As can be seen, the latter mode of operation was the most typical during COVID-19 given the need to combine heating (HS) in winter and air conditioning (AC) in summer with NV to try to alleviate the spread of this respiratory disease [41, 262]. In some studies, where it has not been possible to ensure adequate ventilation by opening windows and doors, it has been decided to combine NV with mechanical ventilation (MV) systems [43].

Figure 7 shows the average neutral and comfort temperatures and their lower and upper limits taken from Table 2 for each climate zone. The temperature limits for the studies conducted under COVID-19 conditions are also included in the dashed line. Thus, neutral temperature can be defined as the temperature at which no heat transfer occurs between the body and the environment. The thermal sensation corresponding to the neutral temperature is indicated by a “0” on the ASHRAE 7-point scale [53, 277], while the lower and upper limits have been considered as the minimum and maximum temperature of the comfort band [28], respectively, recorded in each of the reviewed studies.

Since the investigations were carried out in different seasons and climate zones, using multiple modes of operation in terms of ventilation and air conditioning, the indoor neutral temperature varied greatly in each climate and ranged from 13.90 to 32°C, as shown in Table 2 [88, 154]. As shown in Figure 8, the highest average comfort temperature was recorded in climate zone A (27.78°C), while the lowest average comfort temperature was recorded in zones with type D lime (21.24°C). Also, the comfort band (upper boundary-lower boundary) was the widest (18.40°C) [151] and the narrowest (0.70°C) [211].

In the studies conducted under COVID-19 conditions, the average neutral temperature was 22.45°C, with a comfort range of 10.50°C. Although the limited number of studies published to date does not allow any firm conclusions to be drawn under these circumstances, it can be seen that



	Lower limit (°C)	Neutral temperature (°C)	Higher limit (°C)
Primary	20.46	24.36	25.72
Secondary	20.14	24.04	25.97
University	22.39	24.53	27.57
COVID-19	17.5	22.45	28

Figure 8: Lower and upper limits and mean neutral comfort temperature for different educational levels.

although most of these studies were carried out in climate zone C, the neutral temperature was slightly lower (0.5°C). This slight difference could be because more studies were carried out in winter, which means that the thermal preferences were lower than those established for this type of climate. Also, the influence of stricter ventilation measures led to lower temperatures in the classrooms. On the other hand, the lower limit was also lower (3.36°C) than that established for the type C climate. However, the upper limit was 2.14°C higher. These differences in the limits are mainly due to the small number of samples and the different climates and seasons in which the different studies were carried out during the COVID-19 period, which tends to bias the more extreme values reported in some studies [41, 146].

The neutral temperature ranged between 21.80 and 32°C, with a minimum in air-conditioned classrooms during summer in Ecuador [220] and the maximum in Nigeria [88]; between 13.90 and 27.21°C for climate zone B in China and India, respectively [154, 177]; between 13.90 and 32°C in group C in winter time with NV in China [154] and in Cyprus with AC during summer [178]; and between 18 and 26.80°C in China for climate zone D [168, 185]. In most of the studies, the preferred temperatures did not correspond accurately with the neutral thermal sensation of the respondents.

In studies conducted in climate zone A, mostly in classrooms with natural ventilation during winter and summer, the occupants showed a higher heat tolerance and were better able to adapt to the environment they are used to, even if the thermal and environmental conditions exceed the standards [171, 175, 210]. Although the relative humidity in this climate is quite high, studies have revealed that the influence on thermal comfort is not remarkable [191, 210]. Group B research has been carried out in classrooms primarily with natural ventilation during the summer and mid-seasons, although several studies have looked at thermal comfort conditions throughout the year. The comfort range and neutral temperatures were almost the same compared to studies in climate zone A [78, 150]. Also, comfort levels above the standards have been considered acceptable [177]. On the other hand, the vast majority of work in climate type C was carried out in buildings with natural ventilation or by a combination of other means, during winter, autumn, and spring. This climate zone is characterised by a wide variety of climatic subtypes. Notably, students in locations exposed to wider climatic variations showed greater thermal adaptation than those in areas with smaller thermal amplitudes [149]. Even when outdoor climatic conditions were warmer than average, students' thermal sensations remained within the neutral range [4, 113, 114, 147, 148, 159, 166]. Finally, the work in group D was mostly carried out during the winter and with a combination of natural ventilation and heating system (HS). The comfort range was notably lower than for the other zones, as this climate is characterised by being quite cold all year round [278]. Furthermore, it was noted that the lower the outdoor temperature, the worse the thermal adaptability to the warm environment is considered, while the adaptation to the cold environment is stronger [168].

3.2.4. Education Stage. The selected works are classified based on the educational level into three groups: (1) primary level, students aged 7 to 11; (2) secondary level, students aged 12 to 17; and (3) university level, students aged 18 to 28.

Most of the research was carried out in universities (106 papers), followed by studies in primary school classrooms (58 papers) and secondary school classrooms (43 papers). At the same time, it can be seen that 12 of the papers analysed thermal comfort conditions for primary and secondary school levels together, two of them in secondary and university classrooms, and two others investigated all levels of education considered in this literature review. Most of the papers at the university level were carried out in Asia (53.77%), while research in primary and secondary classrooms was mainly carried out in Europe (46.90%).

Regarding the period of establishment of measures to try to curb COVID-19 infection in educational institutions, more than half of the studies were carried out in university settings (54.17%), while 16.67% were carried out in primary schools and 12.50% in secondary schools. Some studies were also observed that looked at this situation together at various levels of education.

The lower and upper limits as well as the average neutral comfort temperature according to the different educational stages studied are shown in Figure 8. At the same time, the temperature limits for the studies carried out under COVID-19 conditions are shown in a dashed line.

Most of the studies with primary school children were conducted in naturally ventilated classrooms in climate zones C and A, mainly in winter and mid-season. The neutral temperature, defined as the operating temperature, varied between 16.70 and 32°C in different climate zones [75, 88]. In studies before those reported in this review, children were found to be less sensitive to temperature changes than adults, with very different thermal responses [279]. This effect was also observed in the papers reviewed, as can be seen in Figure 8, where the average comfort range recorded for this level of education is lower than for secondary school and university students. On the other hand, several studies have shown that children living in temperate climates, despite having warmer thermal sensations, do not have a preference for cooler environments. The results suggest that these students are more sensitive to higher temperatures than adults, with comfort temperatures 2-4°C lower than predicted by thermal comfort assessment models [66, 68, 81]. The same effect was also observed in several studies conducted in climate zone B [30, 149]. Possible reasons for the lower neutral comfort temperature preferred by children could be the higher metabolic rate per kilogram of body weight, the fact that children do not always adapt their clothing to the wind chill, and the influence of the indoor environmental characteristics of their home environment [10, 28]. In addition, classroom conditions are highly dependent on the thermal preferences of teachers. This prevents the use of adaptive models in schools at this level, as reported in some studies [4]. At the same time, it should be considered that children's school schedules include time for outdoor recreation. This variation in activity levels and the strong relationship with the outdoor climate may also influence the thermal perception of this type of student [66]. Therefore, several authors state that all these parameters need much more research [69]. However, several studies have highlighted the opposite effect for children in climate zone A, where the neutral temperature was higher than suggested by the different standards, especially during the summer season [95, 148]. This may indicate that primary school children are better adapted to the thermal and environmental conditions of tropical climates [280].

The second category of thermal comfort analysis is for secondary schools. Occupants in this age group have a greater ability to adapt to the environment through behavioural actions and the metabolic rate differs less from that of adults compared to primary school pupils [28]. In turn, researchers would be more willing to conduct research with primary school students because of their greater ability to provide more reliable and accurate information about their thermal sensations and preferences [120, 121]. However, this has not been demonstrated in the number of studies carried out. As in the previous case, the studies were mainly carried out in climate zone C, followed by zones A and B, in that order. The work carried out was similarly distributed between the different seasons. Although the age of the occupants, climate, season, and type of ventilation were similar in almost all cases, there are still differences in the thermal sensation [111, 112, 127–129].

The third category analysed corresponds to field studies of thermal comfort in university classrooms. The first thermal comfort studies carried out by Fanger in climatic chambers involved university students [18]. However, subsequent research pointed out the discrepancy between actual and expected thermal sensations as a result of the adaptation actions carried out by students in classrooms [261, 277]. University students generally spend less time indoors than the other two educational levels studied, so thermal perceptions may be different. On the other hand, given their physiological characteristics, the results of studies on thermal comfort in offices could be applied to this type of occupant. However, it has been observed that the neutral temperature is higher in classrooms than in offices. This phenomenon is mainly because office workers are more dressed than students. Therefore, it cannot be assumed that the thermal comfort requirements of university students are the same as those of office workers [159, 281]. Several authors also observed that university students preferred a warmer indoor environment during colder seasons when classrooms were naturally ventilated [240, 241]. It was also found that the range of thermal dissatisfaction was wider than that of cold dissatisfaction. This phenomenon suggests that students have a lower tolerance for hot conditions [167]. Finally, it has been noted that the results of the thermal sensation vote collected in the questionnaires tended to accentuate uncomfortable conditions as opposed to what was objectively measured in air-conditioned classrooms [165].

The results of the COVID-19 pandemic studies indicate that the average temperature in neutral conditions was approximately 2°C lower compared to all educational stages. The lower temperature limit was very close to the values observed at primary and secondary school levels. These data reveal that, although more research was conducted in university settings, the greater weight of lower indoor temperatures recorded during the winter due to excessive ventilation measures to curb COVID-19 contagions had a more noticeable influence [41, 44, 45]. In contrast, the dominance of university studies under these circumstances was evident in the upper limit of comfort, as this is practically the same as for all the studies analysed.

Finally, the thermal environment has been shown to affect thermal preference at all levels [256, 257]. So far, improved living conditions and comfort levels at home have increased the expectation of students in the classroom. Studies show that the comfort temperature in classrooms has increased over the last 65 years [282]. This could be due to higher temperatures in homes due to the extensive use of heating systems. Also, the 1.5°C reduction in the neutral temperature during the last decades in warm seasons is a consequence of the use of air conditioners in homes with hot and humid climates. This could be the main reason for the reported discomfort in naturally ventilated classrooms [80, 147]. However, current trends in ventilation to promote better air quality by reducing the impact of respiratory diseases such as COVID-19 and energy-saving measures in buildings could change comfort levels significantly in the coming years [226, 230].

3.2.5. Thermal Comfort Approach: Compatibility with Models. The choice of the model to analyse thermal comfort in educational buildings is crucial, as it can affect the prediction of wind chill. The studies used different approaches, such as the rational model (49 studies, 21.97%), the adaptive model (46 studies, 20.63%), a combination of both (57 studies, 25.56%), and other indicators (71 studies, 31.84%), as shown in Figure 9. Each model can reach different conclusions about the thermal state of students, so it is important to select the model that best fits their characteristics and needs, reflecting their true thermal sensation [23].

Concerning the approach used in the COVID-19 studies, most of the studies (70.83%) have been carried out using methods other than the rational and/or adaptive approach.

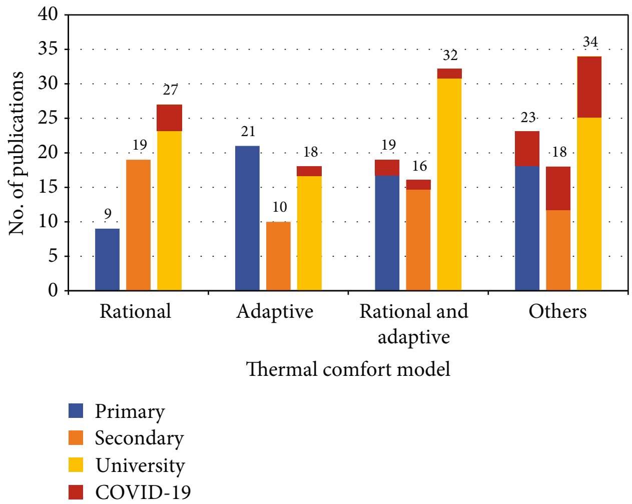


Figure 9: Publications on different approaches to thermal comfort according to educational level.

This is because most of these studies focus on assessing how natural ventilation conditions have influenced ambient temperature and relative humidity, thus evaluating thermal comfort only with these parameters [44, 47, 239].

As discussed above, the rational approach consists of the traditional Fanger PMV index calculation model [18]. Among all the studies reviewed, this method has been widely used in thermal comfort assessments in universities. However, in most of the work carried out for all educational levels, this approach was used in conjunction with the adaptive model. This indicates that for a complete and comprehensive analysis of thermal comfort conditions in classrooms, it is necessary to deal jointly with the objective measurements of the rational approach and the subjective responses of the adaptive approach [21, 261].

Figure 10 shows the compatibility of the two methods according to climate zone. As can be seen from the studies reviewed, the compatibility with the rational approach is generally low for all climate zones. For the dry climate, no work has been found that shows a correlation with Fanger's method. For climate zone C, most of the studies underestimated the real sensation perceived by the pupils. On the other hand, a better fit of the adaptive approach can be observed for all climates, especially for climate zones A and C. This effect has been reported in several studies [28, 154].

Figure 11 shows the fit of the rational and adaptive approach with the TSV according to the different seasons of the year. For all seasons, low compatibility with the rational model is again shown. Also, for the middle seasons, a higher level of overestimation of the real thermal sensation of the students is observed. Although the adaptive model was found to be much more compatible in all cases, there are a considerable number of studies where a lower acceptability than the real wind chill was found, mainly during the summer. This effect could be due to the widespread use of air conditioning in certain climates during this season [80, 147, 186].

The correlation of the rational and adaptive approaches with the TSV index as a function of educational level is shown below. Of the reviewed papers using the rational approach (Figure 12(a)), the majority (48.70%) indicated that the model underestimated students' thermal sensations, 41.00% reported overestimation, and only 10.30% indicated that the thermal comfort predictions were compatible with students' actual thermal sensations across all educational levels. Underestimation was mainly found in primary school classrooms, while overestimation was mainly found at the university level. This approach showed a slight overlap at all levels, especially for children, where no work has shown acceptance. This effect is due, as already mentioned, to the fact that this approach is only valid for adults under constant conditions [69, 283].

In educational centres, unlike other types of buildings, it is possible to have greater control over the parameters affecting the conditioning of individual classrooms during school hours [23, 28]. Therefore, the adaptive model could be a more accurate method for assessing thermal comfort in classrooms. This approach was used in most of the reviewed studies. Compatibility with adaptive standards and comfort equations was also observed in several studies. Figure 12(b) shows the study of the compatibility of the adaptive model in the different reviewed publications according to the educational level.

Of the studies using the adaptive model, 33.30% reported lower comfort levels compared to standards, while 28.20% reported higher neutral temperatures. Most studies (38.50%) showed compatibility with the adaptive approach, particularly at the university level.

In some cases, the results reflected that students were well adapted to the local climate and showed adaptive behaviours such as adjusting clothing, operating windows, and even using fans [29, 113, 145, 149, 160, 217]. It should be noted that the results show that human thermal sensations are related to both indoor and outdoor climates. Therefore, the adaptive model also cannot accurately predict the thermal sensation of the occupants, as it only uses the outdoor temperature to predict the comfort temperature [261, 284]. Furthermore, the neutral temperature of the students was found to be 4-5°C lower than that predicted by the rational model and about 2°C lower than that corresponding to the adaptive comfort limits in EN 15251 and ASHRAE 55 [53, 54].

Therefore, it can be concluded that in all climate zones, seasons, and educational levels, there was a high degree of discrepancy between the predicted mean vote and the actual thermal sensation of the students, especially in nonclimatised environments. Also, the adaptive method was not accurate in most cases, as it only takes into account the effect of temperature. Thus, it could be argued that the two approaches to thermal comfort are complementary rather than contradictory [23, 261], and the joint application of the two models would be useful to obtain more accurate results. At the same time, it has been pointed out that the standards are not directly applicable due to the differences in the temperatures they capture, which are also the same for all climates. For this reason, some authors have pointed

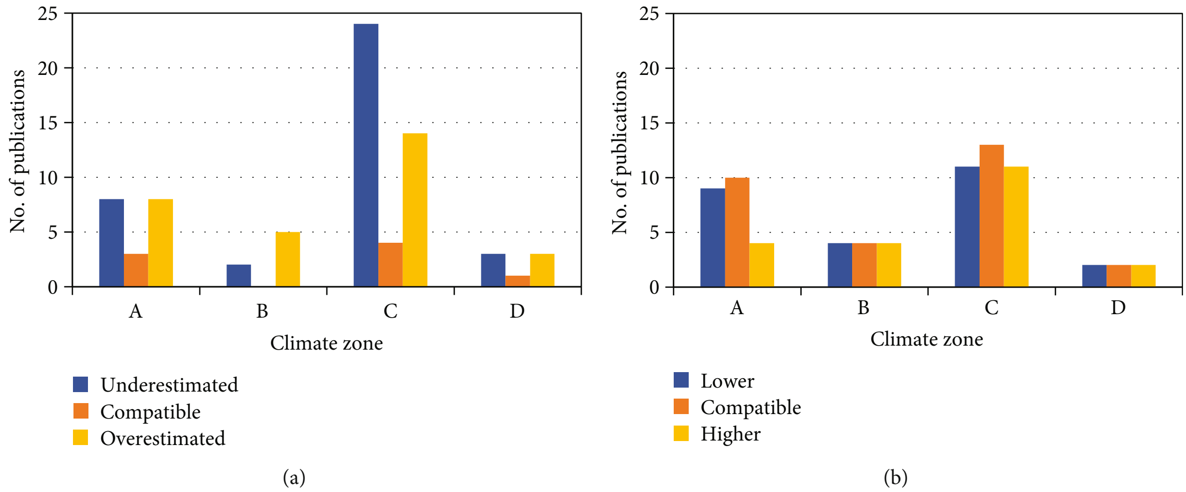


FIGURE 10: Compatibility of TSV with the rational (a) and adaptive (b) approach in different climate zones.

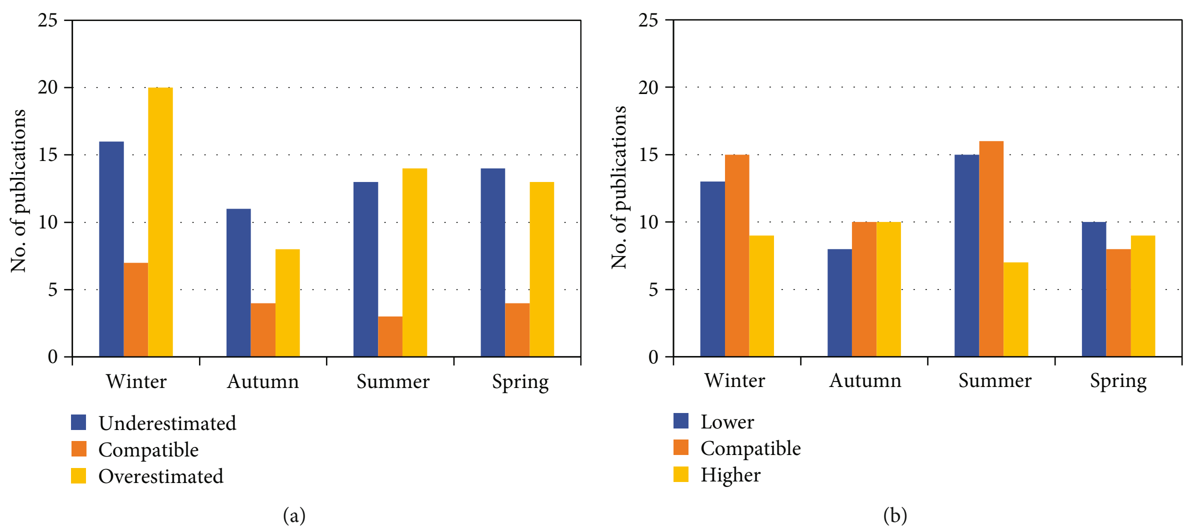


FIGURE 11: Compatibility of TSV with the rational (a) and adaptive (b) approach in different seasons.

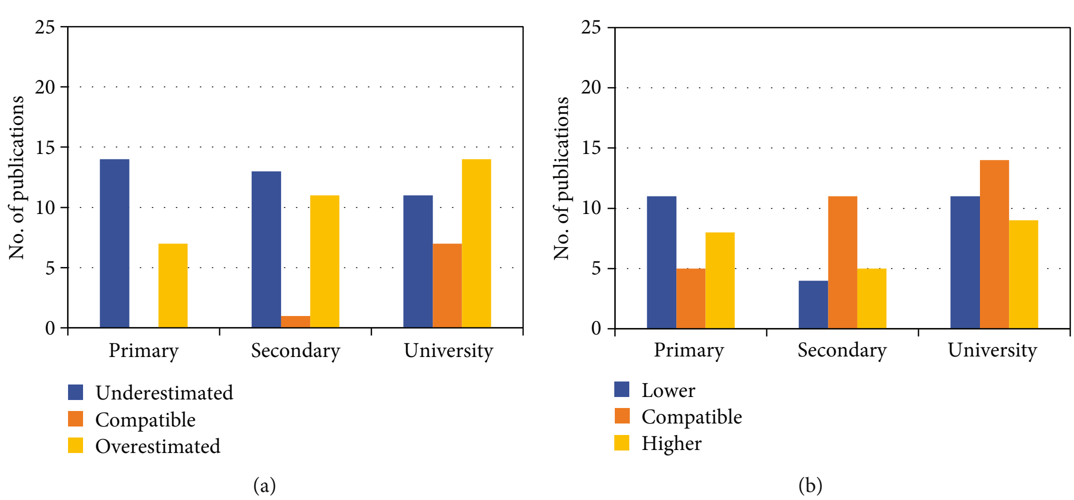


FIGURE 12: Compatibility of TSV with the rational (a) and adaptive (b) approach by educational level.

out that for a standard to be truly valid and considered international, coordination between countries and a common agreement process is required [285]. It would be desirable for researchers in this field around the world to compile and analyse more up-to-date databases of studies in different climates and educational levels, taking into account cultural, technological, and energy differences, to revise the standards and provide reliable comfort temperatures using meta-analysis tools.

Regarding the compatibility of thermal comfort assessment methods in COVID-19 research, not enough papers have been found to conclude, as can be seen in the table in Table 2. Of the 24 papers collected under these circumstances, only two refer to information on this point. The authors of both papers pointed out that the rational method underestimated the thermal sensation of students at all educational levels [251, 257], while one of them found the TSV compatible with the adaptive approach [257].

3.2.6. Adaptive Thermal Comfort Equations. This section explores how the comfort temperature varies with the average outdoor temperature from a selection of the literature reviewed in which these indices are evaluated. It is also tested whether these temperatures are within the two ranges of acceptability calculated according to ASHRAE 55 [53]. Figure 13 shows the comfort temperatures and outdoor air temperatures during the voting time proposed by different studies, together with the adaptive ASHRAE 55 model indicating the upper and lower temperature limits of the comfort zone. Additionally, it can be seen that by performing the regression analysis the adaptive comfort equations shown are obtained, one for each educational level, one for the total set, considering primary, secondary, and university at the same time, and one for the pandemic conditions by COVID-19.

To create this graph, the proposed comfort temperature data, in terms of operating temperature and measured outdoor temperature, were extracted from the articles that dealt exclusively with the adaptive method or together with the rational approach. In this way, 50 papers were selected, representing 22.42% of the total.

Firstly, it can be seen that the comfort temperature increased as the outside temperature increased. A higher correlation between the two temperatures was found in the NV classrooms. This effect has also been observed in other studies [10]. In most of the studies analysed, the comfort temperature was found to be within the 80% acceptability range (88.00%, 44 papers). Of these, 42 were also in the 90% range. At the same time, the sensitivity to changes in outside temperature varies according to the different stages of education. Primary school students were the least sensitive to temperature changes. This could be since the choice of adaptation measures and the level of clothing depends mainly on adults (teachers and parents) [10, 27, 150, 168]. On the other hand, secondary school students were the most sensitive to changes in outdoor temperature. The equation resulting from the temperatures recorded in the studies with university students shows a slope close to that of the ASHRAE 55 standard, whose expression is $T_c = 0.31 \cdot T_{out} +$

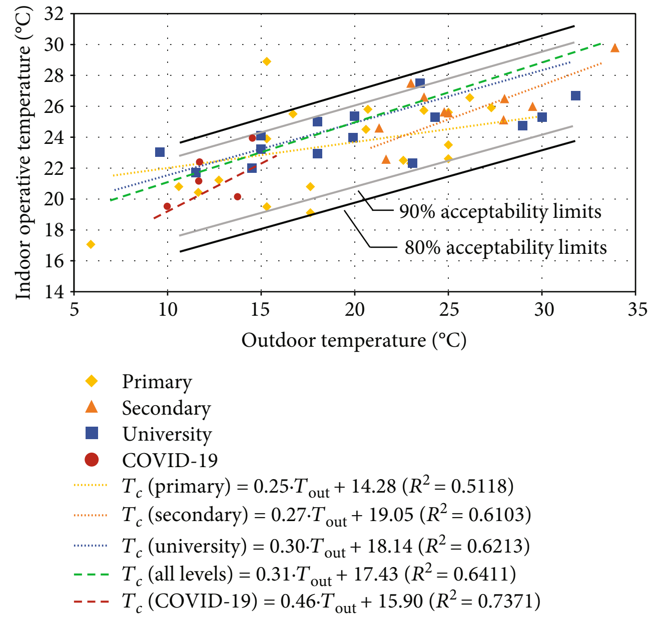


Figure 13: Comparison of comfort temperature with ASHRAE 55 adaptive model.

17.80 [53], obtained from a large amount of data extracted from field studies where the participants were healthy adults [21]. This proximity is mainly because university students fall within this age group. In addition, university students tend to have more freedom to choose their coping strategies [10]. The equation obtained for all levels of education also has a very similar slope to the ASHRAE standard, which also shows the greater influence of the set of studies conducted at the university level on the others.

On the other hand, four of the studies fell outside both ranges. The latter situation is an indication that the choice of the adaptive method was not the most appropriate for the analysis of thermal comfort in these studies. It can be seen that in three of the cases, the average outdoor temperature recorded was less than 10°C, and one of the studies was almost 5°C below the limit set by the ASHRAE 55 standard [92]. Furthermore, in one of them, heating use was found to be an additional deviation from the applicable standard [209]. On the other hand, a high outdoor temperature has a direct effect on the working temperature. In this case, the use of air conditioning would have been necessary to achieve a comfortable temperature within the range. Therefore, it could be said that the results of these studies are not supported by the thermal comfort standards [53].

Finally, the slope of the curve is very different when only the COVID-19 work is considered. In these cases, there was a greater influence of the outside temperature on the comfort temperature due to the natural ventilation strategies imposed to prevent the spread of the SARS-CoV-2 coronavirus. It should also be noted that despite outside temperatures below 15°C, all but one of the recorded values were within the comfort range. This may indicate the importance of establishing window-opening and closing strategies when CO_2 concentrations are appropriate [41].

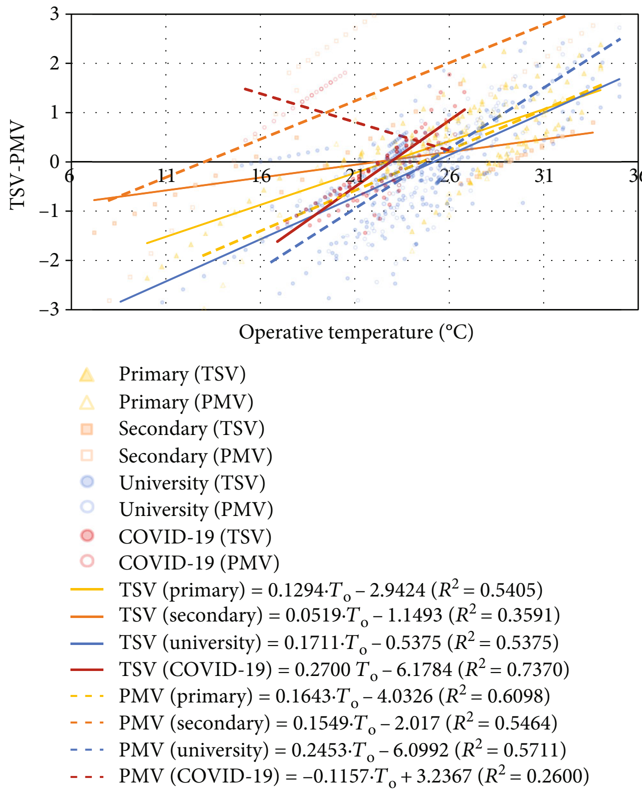


Figure 14: PMV and TSV ratio vs. operating temperature, by educational level.

3.2.7. Regression Equations of Thermal Sensation Vote (TSV) and Predicted Mean Vote (PMV). Figures 14 and 15 show the correlation between the PMV and TSV indices obtained from the thermal sensitivity of the students, as a function of the operating temperature conditions and the insulation coefficient of the clothing, for a selection of the works analysed in this literature review. This analysis has been carried out for the different educational levels and climatic zones, respectively. However, it has not been possible to study the relationship between both indices as a function of season and type of ventilation/air conditioning due to the lack of data from the field works reviewed for some of the variables. Both figures also show the regression line of these indices for the work carried out during the pandemic period by COVID-19.

The data were also analysed statistically including the corresponding linear regression equations shown in both figures. The thermal insulation of students' clothing in the set of all selected thermal comfort field studies was between 0.3 clo (0.05 m^2K/W) and 1.5 clo (0.23 m^2K/W).

First of all, Figure 14 shows a clear "scissors difference" phenomenon between TSV and PMV in secondary school classrooms. The greater variability of seasons and climatic zones in which the studies for this educational level were carried out may be the cause of this difference. This variability may also reflect the use of different ventilation and/or air conditioning systems. For these reasons, both the thermal environment and the students' acceptance were not strictly in a steady state [154]. The slope of the regression line of the PMV is greater than that of the TSV. This indicates that the students' cold tolerance was higher than predicted [113, 120, 121]. Students were generally not as sensitive to temperature changes as expected and were able to perform different actions to adapt to both cold and warmer environments [111]. Therefore, this analysis confirmed that the PMV was still not able to accurately predict the average thermal sensation of adolescent students [129]. The operating temperature range in which both equations were defined was between 7.5 and 33.5°C. The greatest difference was found at this level of education. When TSV and PMV were equal to zero, the corresponding indoor temperature was represented by the neutral comfort temperature [217]. Thus, for the secondary school studies, it can be observed that the temperature at which comfort was reached in the case of the PMV regression equation was 18°C, whereas, for the TSV, it was 23.5°C, i.e., in line with the above, the rational approach underestimates the real choice of this type of occupant [28]. On the other hand, the operating temperature range for the primary studies was about 10-34°C, which is slightly lower for the PMV equation. The comfort temperature for the TSV was 22.5°C, while for the PMV, it was slightly higher (24°C). For the university stage, a similar range of temperatures was observed for the TSV, ranging from 8.5 to 35°C. However, the lower limit of the range was 16.5°C. The neutral comfort temperature, in this case, was practically the same for both indices (25°C). Finally, the regression coefficient of the fitting equation (R^2) reflects the sensitivity of the thermal sensation of the occupants to temperature

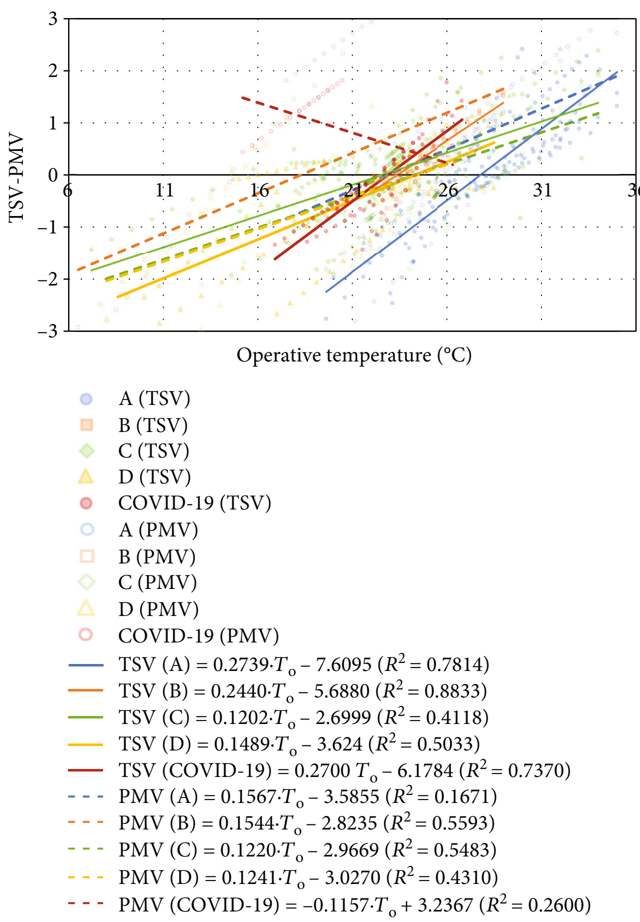


Figure 15: PMV and TSV ratio vs. operating temperature, by climate zone.

changes. Thus, the average regression coefficient obtained for the TSV and PMV equations is about 0.5274, indicating that about half of the dependent variable (operating temperature) is predicted by the independent variables (PMV and TSV). Therefore, the fit obtained for all studies in this analysis can be considered acceptable [112].

Next, Figure 15 shows that the highest slopes for the TSV and PMV equations were obtained for climate zone A (tropical or macrothermal climate). The range of operating temperatures was similar in both cases, from 18 to 35°C. On the other hand, for the dry climate (climate zone B), there is a large difference between the straight lines representing the TSV and the PMV. The temperature range for TSV is much lower (22-28°C) than for PMV (7-28°C), with the slope of the resulting regression line being much steeper in the former case. This phenomenon could be a result of the fact that the PMV study was carried out at all seasons, whereas the TSV analysis concentrated on seasons with higher temperatures. In climate zone C, the lines resulting from the fitting equations are parallel, with the one corresponding to the TSV expression being slightly higher. The neutral temperature for this index is therefore lower (22 °C) than for the PMV (24 °C). However, despite these differences, the comfort range was the same in both cases (7.5-34°C). The large amplitude in the temperature range would be due to the existence of a large variety of climatic subtypes within this zone and the differences between seasons [275]. Continental climates (climate zone D) are characterised by very low outdoor temperatures throughout the year [278, 286], so it can be observed that indoor operating temperatures below 20°C prevailed for both TSV and PMV. This was mainly the case in educational buildings without heating systems [39, 47, 92]. Both the temperature range (7-27°C) and the comfort temperature (24°C) were very similar in this case. The mean regression coefficient for the resulting TSV equations ($R^2 = 0.6449$) was higher than for the PMV ($R^2 = 0.4264$), with this difference being more pronounced for climate zones A and B. These results continue to question the rational method as a method for assessing occupant thermal sensation [23, 28].

Lastly, both graphs show the regression lines for both TSV and PMV for all the studies carried out during the COVID-19 pandemic. Although the number of publications to date is small, the first thing that stands out is the large difference in the slope of the two lines, although most of the research was carried out during the winter. This could be because the studies in which the PMV equation was derived used heating systems [251, 257]. For TSV, the neutral temperature was set at around 23°C, whereas for PMV, it is assumed to be much higher. The presence of a more noticeable air velocity, especially when natural cross-ventilation was used, could result in a higher temperature necessary for students to stay within the thermal comfort range. As for the regression coefficient, the regression line was significantly better fitted for TSV ($R^2 = 0.7370$) than for PMV ($R^2 = 0.2600$). This discrepancy could be due to the simultaneous use of heating and window opening since the rational approach is specifically designed to be applied in rooms conditioned exclusively by HVAC systems [18, 287].

As shown in the cases analysed above, the correlations obtained are somewhat lower than those proposed by other authors. This could be because, in this study, data corresponding to different buildings, classrooms, or climatic conditions are analysed in a combined way. However, despite the problems associated with studying a large number of papers with very diverse characteristics, this observation has made it possible to provide relevant information on the trend of the parameters analysed.

4. Conclusions and Future Research

Thermal comfort can be considered a fundamental requirement for the well-being of students and teachers in classrooms and is key to improving learning and productivity, and its analysis has become particularly relevant in recent years. The purpose of this paper is to present a comprehensive literature review of field studies on the assessment of thermal comfort conditions in schools over the last 25 years. For this purpose, 223 research studies published in peer-reviewed scientific journals and international conference proceedings were selected. More than 10% of these studies focused on the analysis of thermal comfort conditions in the context of the global COVID-19 pandemic.

Throughout this study, the two approaches used to analyse thermal comfort have been identified and discussed in detail. In many of the studies, the indices derived from the rational model have not been correctly adjusted to the environmental conditions. This effect is mainly reflected in the studies carried out in dry climates, where no correlation between PMV and TSV has been shown in any of the studies. On the other hand, the adaptive model proved to be more suitable for the study of thermal comfort in classrooms, as it takes into account the needs of different groups of people, such as children and adolescents.

The neutral temperature defined in terms of operative temperature varied between 16.70 and 32°C in different climatic zones. Thus, the literature has shown that individuals living in places with larger temperature ranges throughout the year show thermal adaptability. However, the widespread use of HVAC systems has led to lower acceptability than the actual wind chill in some climates.

Primary school children were less sensitive to temperature changes. At the same time, it was observed that children had a warmer thermal sensation, although they did not prefer cooler environments. In contrast, secondary school and university students showed a greater degree of dissatisfaction with heat than with cold.

In many cases, thermal comfort questionnaires have been conducted in specific seasons with a limited number of respondents. Therefore, studies should be conducted throughout the school year with a larger number of participants to obtain generalised comfort temperature ranges. However, studies conducted within the same climatic zones have shown large variability in thermal neutrality. This highlights the need for smaller-scale thermal comfort studies. Our recommendation to improve the usefulness of such studies is that more resources should be devoted to increasing sample sizes and making them longitudinal in nature, not necessarily increasing the geographical scope of the study.

As far as the applicable standards are concerned, a large proportion of the studies reported lower comfort levels than those stated in the standards. This indicates that the standards used turned out to be not very suitable for the assessment of thermal environments in classrooms. Furthermore, the neutral temperature of the students was found to be 4°C lower than that predicted by the rational model and about 2°C lower than that corresponding to the adaptive comfort limits of the EN15251 and ASHRAE 55 standards. Thus, the results indicated that these regulations are not directly applicable to thermal comfort assessments in classrooms of different climates and educational stages. We believe it is desirable to create new regulations that are adaptable to all contexts, considering changes in the climatic environment as well as in the characteristics and habits of the occupants.

Finally, most of the studies characterised by the COVID-19 disease were carried out in temperate climates during the winter. It should be noted that both the calculated neutral temperature and the comfort band were dominated by the extreme values reported in the different studies. Also, the outdoor temperature was more dominant in obtaining the comfort equation due to the strong influence of natural ventilation in these cases. However, almost all the studies were within the comfort range, making it clear how important it is to establish correct ventilation strategies adapted to the existing air quality.

Based on the above, as possible future lines of research, it is proposed to study more refined adaptive comfort models that include specific control systems designed to take occupant preferences into account. Such models will allow progress in the analysis and optimisation of energy systems and demand management, so important today because of ongoing developments such as the ventilation measures put in place to curb the spread of respiratory diseases such as COVID-19, the global energy crisis, and global warming. The development of spatial and temporal thermal comfort metrics could be useful for thermal comfort assessments, especially in classrooms where students are subject to occupying a fixed position during class time, which is mainly the case for primary and secondary school students. It would be interesting, in addition to general thermal comfort assessments, to study local discomfort to reduce the percentage of dissatisfaction in indoor spaces and to assess its impact on indicators of students' academic performance.

Abbreviations

AC: Air conditioning
AMV: Actual mean vote
APD: Actual percentage dissatisfied
aPMV: Adaptive mean vote
cPMV: Corrected mean vote
DISC: Discomfort index
ePMV: Extended predicted mean vote
ET*: Effective temperature
FR: Free running
T_g: Globe temperature
HIS: Heat stress index
HS: Heating system
HSV: Humidity sensation vote
MM: Mixed mode
MSV: Mean sensation vote
MV: Mechanical ventilation
NV: Natural ventilation
OC: Overall comfort
PD: Percentage dissatisfied
PPD: Predicted percentage of dissatisfied
PMV: Predicted mean vote
RH: Relative humidity
SET*: Standard effective temperature index
T_a: Air temperature
TAV: Thermal acceptability vote
T_c: Comfort temperature
TCV: Thermal comfort vote
TIP: Thermal interference in the students' performance
T_n: Neutral temperature
T_{op}: Operative temperature
T_{out}: Outdoor temperature
TPV: Thermal reference vote

T_{rm}: Mean radiant temperature
TSaV: Thermal satisfaction vote
TSV: Thermal sensation vote.

Data Availability

The data supporting this review are from previously reported studies and datasets, which have been cited.

Additional Points

Highlights. (i) Combining rational and adaptive methods makes thermal comfort studies more reliable. (ii) Current standards are not adapted to evaluate thermal comfort at educational stages. (iii) Children are less temperature-sensitive; higher education students are more heat-tolerant. (iv) Students from regions with greater climatic variations showed better adaptation. (v) COVID-19 ventilation impacted well-being and increased thermal comfort research.

Conflicts of Interest

The authors declare no conflict of interest relating to the material presented in this article; its contents, including any opinions and/or conclusions expressed, are solely those of the authors.

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