

Review

Thermal Comfort in Classrooms in NSW Australia: Learning from International Practice: A Systematised Review

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Abstract

International thermal comfort requirements, such as ASHRAE standards, are used for classroom design in many countries, such as Australia, despite these standards serving thermal preferences for adult office workers in the USA or Europe. Subjected to mismatched thermal guidelines, students can be thermally uncomfortable in classrooms that are not correctly designed for their needs, and education buildings may consume significant energy on heating and cooling that is not appropriate to the location. The objective of this study is to critically examine the appropriateness of ASHRAE thermal comfort standards for classrooms in climates equivalent to New South Wales, Australia. Through a systematised literature review, this paper presents findings in four key areas: the relationship between thermal comfort and (i) local climate areas, (ii) classroom building types, (iii) students' thermal comfort preferences and (iv) air conditioning. The research finds that international thermal comfort standards do not always provide suitable guidance for classrooms in diverse climate zones. The research identifies that reliance on mechanical heating and cooling can fail to meet students' thermal comfort needs and undermines global environmental sustainability goals. This paper recommends localised thermal comfort benchmarks tailored to NSW's climatic and educational contexts, contributing to improved classroom design, student wellbeing and energy-efficient learning environments.



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1. Introduction

The current impacts of global warming include increased ambient air temperatures. With the last ten years being the hottest on record globally, temperatures are predicted to continue to rise [1]. The increase in land temperatures corresponds to a rise in indoor thermal air temperatures, leading to increasing energy consumption from the ventilation and air conditioning used to address the consequential reduction of thermal comfort [2]. Defined as the “condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation” [3] (p. 3), the term thermal comfort describes a person's psychological response to the level of heat and humidity in a building [4]. Thermal comfort is one of the main factors in the operational settings of air conditioning systems, as occupants seek comfortable indoor thermal environments [5]. Because mechanical air conditioning has high energy demand and can release additional greenhouse gasses (beyond

operational carbon), achieving levels of thermal comfort can significantly impact energy consumption in buildings [6,7] as well as levels of greenhouse gas emissions [8].

Thermal comfort affects different building users in different ways. In school environments, increased heat in classrooms has been shown to negatively affect student learning [9]. However, cooling classrooms with constant air conditioning does not provide good air quality, as the recirculated air retains CO₂, causing drowsiness of students, reducing their learning capacity [6]. Internationally, successful thermal comfort in classrooms has been associated with achieving the Sustainable Development Goals (SDGs) [10], and the SDG goals 3, 4, 7, 9, 11, 12 and 13 have been mapped to thermal comfort in classrooms [11].

School education is compulsory for children at primary and secondary levels in Australia, with children spending about ten years in this early education phase. To ensure thermal comfort is met for students in Australian classrooms, assessing classrooms against guidelines and regulations for thermal comfort would be the expected place to start. There are two international standards used in Australia to assess thermal comfort, the ASHRAE and ISO standards, which originate from the USA and Europe, respectively. These standards differ slightly, so the more commonly used ASHRAE is the focus for this research. Problematically for thermal comfort of classroom environments in Australia, these international standards are based on the thermal preferences of adult office workers in Europe and America rather than localised thermal preferences of children in classrooms in nations worldwide [12–14].

Thermal comfort of individuals relates to the local climate, occupant activities and needs of unique occupants [15]. Establishing thermal comfort for students in classrooms involves complex inter-relationships between thermal comfort measures, climate zones, building types and use, as well as the thermal preference of children and impacts of air conditioning, all in the context of a climate-changed world. When thermal comfort standards such as ASHRAE are applied in a blanket approach to primary and secondary education buildings internationally, issues are raised by academics in separate but related (and sometimes overlapping) areas of research inquiry. Our initial literature review categorises these issues as (i) models do not include precise local climate variations of school locations [16–18]; (ii) the variety of activities carried out in classrooms do not relate to modelled office worker activities [12,19,20]; (iii) children have different thermal preferences to adults [9,21,22]; and (iv) air conditioning affects learning in classrooms and contributes to carbon emissions [19,23,24].

The aim of this paper is to contribute to the local and global understanding of the appropriateness of ASHRAE thermal comfort standards for classrooms in climates equivalent to New South Wales, Australia. As Australian-based information is limited, this research learns from the experiences of other nations. To ensure a similar climatic framing in our search, we selected sources for the systematised review from the same climate as NSW, Australia, which, according to the Köppen–Geiger system, has arid and warm temperate climate zones [25]. We further limited our sources to nations outside of the USA who find themselves in a similar situation as Australia, being bound to national standards based on US climate, culture and occupancy. Our research details the methods that researchers in these locations are using to understand thermal comfort in classrooms, the current thoughts on the importance of local climate in thermal comfort assessment and suggested optimal thermal settings. Delving into the relationships between the setting and context of students and classrooms, this research provides a comprehensive synthesis of current academic thoughts on the significance of thermal comfort, focusing on four key areas: local climate zones, classrooms, students and air conditioning. The paper begins with an extensive background literature review, starting with the theory of thermal comfort standards. While the literature is drawn from a global perspective, the research also considers the application

for government-run primary and secondary schools in NSW, Australia. This first part of the paper review draws together government and industry regulation documents with overviews of academic positions on different topics to build a clear picture of this complex issue. Thermal comfort in classrooms is not only essential for student health and cognitive performance but also has significant impact on energy consumption in educational buildings. This study addresses the gap in the existing research by examining the literature and evaluating the applicability of ASHRAE standards to education buildings and students in diverse climate zones. The objective of this study is to critically examine the appropriateness of ASHRAE thermal comfort standards for classrooms in climates equivalent to New South Wales, Australia.

2. Background

2.1. Thermal Comfort and PMV

Thermal comfort is a measure of how an individual feels about the thermal conditions of their immediate environment, usually in a building. To maintain thermal comfort, an individual may be able to adjust their clothing or adjust their space by opening or closing windows, using blinds, turning on fans, heating or air conditioners; however, the ability to make adjustments can vary depending on the culture and situation [16]. Thermal comfort varies between individuals, and with more than one person in the room, there are a range of thermal preferences to be met, and it has been identified as a challenge to find an optimal indoor thermal environment for all people in a given room [26,27]. Yet, if the room settings do not match occupant needs, discomfort and other effects, such as the ability to concentrate and mental and physical wellbeing, are affected. Research into the variation in thermal comfort was popularised in the late 1960s by Povl Ole Fanger, resulting in predictions of thermal preferences for a set of people in a space. Despite existing for over 50 years, few alternatives have been taken up, despite some advances in Fanger's work [28,29].

Thermal comfort research and practice considers building and human variables such as the climate zone, building type, and occupant activities [30]. There are currently two models to evaluate thermal comfort in a built environment: the Rational Thermal Comfort (RTC) model based on Fanger's work and the Adaptive Thermal Comfort (ATC) model, a deviation from Fanger's work. At present, the RTC model is the most common way to predict thermal comfort in mechanically ventilated buildings. This model (which encompasses the Predictive Mean Vote index (PMV)) is based on laboratory data from climate chamber studies to support its theory [31]. The RTC model provides thermal comfort predictions for mechanically ventilated buildings that are very close to the thermal sensations experienced by people in the actual space [32]. For less controlled environments, such as naturally ventilated buildings, the Adaptive Thermal Comfort (ATC) model is typically applied. Based on the idea that outdoor climate influences indoor comfort, the ATC model uses data from field studies of people in buildings to define levels of thermal comfort and uses an "acceptability limit" rather than the PMV index [33].

The development of the Predictive Mean Vote (PMV) model was a significant milestone in thermal comfort research [34,35]. Predicted Mean Vote (PMV) represents the mean thermal comfort level on a standard scale, mathematically predicted for a group of building occupants based on the combination of air temperature, radiant temperature, air velocity, relative humidity, human metabolic rate and clothing insulation level in a room [36]. The calculated result predicts the thermal sensation of the room's occupants via a range of numbers between -3 (cold) and $+3$ (hot), where the optimal thermal comfort level is 0 (neutral), as shown below in Figure 1.

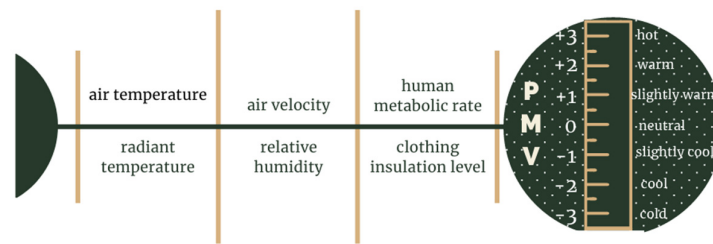


Figure 1. PMV and thermal sensation (figure by the authors).

Predicted Percentage Dissatisfied (PPD), a mathematical function of PMV, is an index that establishes a quantitative prediction of the percentage of thermally dissatisfied occupants, where -3 or $+3$ PMV equals 100% PPD (i.e., too hot or too cold). It has been proposed that PPD, together with a PMV value, can provide a quantitative prediction of the number of people that will be dissatisfied with a certain ambient atmosphere [34]. Key international thermal comfort standards, such as ASHRAE 55 [37] and ISO 7730 [38], recommend that all occupied areas in a building should be kept below 20% PPD in order to ensure thermal comfort. PMV-PPD is now the most widely used index to evaluate thermal comfort in mechanically ventilated buildings internationally [9,35,37,38], including in Australia.

In naturally ventilated buildings, the ATC model provides an “acceptability limit” that relates to the indoor and outdoor temperatures. Based on a global database of 21,000 measurements taken primarily in office buildings [37], the acceptability index includes two sets of operative temperature limits: one for 80% acceptability and one for 90% acceptability. This acceptability limit is the most widely used to evaluate thermal comfort in naturally ventilated buildings internationally [9,28], including in Australia.

2.2. Thermal Comfort Standards

ASHRAE was previously known as the American Society of Heating, Refrigerating and Air-Conditioning Engineers, but now as an international organisation, they are known by their acronym. ASHRAE focuses on “advancing human wellbeing through sustainable technology for the built environment” and publishes built environment standards that are taken up by governments and regulatory bodies worldwide [37]. Their standard for Thermal Environmental Conditions for Human Occupancy of buildings is ASHRAE 55 [37]. The International Organization for Standardization (ISO) “develop voluntary, consensus-based, market-relevant International Standards that support innovation and provide solutions to global challenges” [38]. Their standard for Ergonomics of the thermal environment is ISO 7730 [38].

Both ASHRAE 55 [37] and ISO 7730 [38] provide definitions, requirements and parameters that need to be met for thermal comfort in buildings, and both use PMV and PPD to evaluate and describe indoor thermal comfort. To comply with ASHRAE 55 in mechanically ventilated buildings, the thermal limit is required to be between -0.5 and 0.5 PMV, no matter what the context of the building. ISO 7730 expands on this limit, providing several indoor environment ranges, depending on the building context [39]. ISO 7730 defines the limit for most buildings as ranging between -0.2 and $+0.2$ PMV (class A category), while for old buildings, the acceptable comfort limits range between -0.7 and $+0.7$ PMV (class C category), and new buildings range between -0.5 and $+0.5$ PMV (class B category).

2.3. Thermal Comfort Standards for Buildings in Australia

The PMV-PPD and ATC measures inform thermal comfort standards internationally through ISO7730 (PMV-PDD) and ASHRAE (PMV-PDD and ATC). While different nations have their own standards for many aspects of building and construction, for thermal comfort, most nations use the international ISO and ASHRAE standards. However, per-

sonal preferences for thermal comfort can vary across different climate zones, including in different parts of Australia [16,40]. Despite the ISO and ASHRAE standards originating from Europe and the USA, respectively, and being based on the climate, culture and people of those nations, which may vary dramatically from other parts of the world, these standards are applied worldwide, including in Australia, where they are included in compliance by regulatory and certification bodies in Australia nationally including the National Construction Code and Green Star [16,41].

The Australian National Construction Code (NCC) sets out the minimum standards for the design, construction and performance of buildings in all of Australia's states and territories, and it is produced and maintained by the Australian Government's Australian Building Codes Board (ABCB). Section J of the building code of Australia describes the details on energy efficiency, which have mandatory compliance across Australia. Green Star is a voluntary sustainability rating system for buildings developed by the Green Building Council of Australia (GBCA) in Australia in 2003. The Green Star rating system is categorised in eight basic areas: Positive, Responsible, Resilient, Places, People, Nature, Leadership and Healthy [42]. Indoor Environment Quality (IEQ) is a key aspect of sustainable building performance, and thermal comfort criteria are part of the health category in Green Star.

2.4. Climate Zones

Australia, with a large land mass, has a range of climate zones. The Köppen–Geiger climate classification, one of the most widely used approach to grouping climate zones [43], identifies four main climate groups across all of Australia. New South Wales (as one state within Australia) contains two of these climate groups, the arid climate (Group B) and the warm temperate climate (Group C). The Australian National building code, however, defines eight climate zones, which do not correspond exactly with the Köppen–Geiger system but are similar. The NCC-recognised climate areas range from zone 1 = high humidity summer and warm winter (located in the most northern parts of the country) to climate zone 8 = alpine (located in the southeast corner of Australia) [44].

In recognition of different climate zones, ASHRAE's development of its guidelines for thermal comfort requirements does take different global climate zones into account in its models and standards, using the Köppen–Geiger climate classification system [43]. However, issues have been identified with ASHRAE's climate zone approach. Defining adequate climate zone criteria and the resulting climate zone boundaries is crucial for scientific input into thermal comfort and improving building energy efficiency [17]. However, the ASHRAE method does not always allow for the inclusion of different climatic features, grouping some nations into one climate zone [18], even if they are large nations like China or Australia, which self-identify with several climate zones [41,45]. Furthermore, the prevailing methodology, as used to determine climate zones in the ASHRAE guidelines, may exhibit limitations in accurately distinguishing between distinct climatic characteristics. This has been identified as problematic by Walsh et al. [17], who claim that the climate zones used by ASHRAE are misclassified, resulting in building energy policies not being suited to the actual climates they are applied to. In Australia, ASHRAE provides one climate zone for the entire nation, despite the Australian Building Codes Board and the Köppen–Geiger climate classification system defining more than one climate zone. Likewise, despite the range of climate zones across Australia, section J of the NCC uses blanket PMV requirements regardless of location, even though there are different versions of section J referred to for states including NSW, TAS and NT for other considerations of this energy efficiency section of the NCC [41].

The Köppen–Geiger system is not the only climate classification system. There are multiple climate zones defined around the world, and these climate zone boundaries are important factors in many climate-related classification frameworks [13]. It has been found that discrepancies can arise due to versions of the Köppen–Geiger climate maps and geolocations of buildings within climate boundaries used in different studies [43]. Furthermore, climate change and the effects of urbanisation are recognised as changing the conditions in local climate zones [45]. The alignment of building energy performance with the anticipated climatic conditions within the zones in which these structures are situated emerges as a concern [16], highlighting the necessity for the development of thermal comfort models that are attuned to these considerations and why climate zones are included as a key topic in the systematised review for this study.

2.5. Thermal Comfort in Educational Buildings

Buildings are typically classified by type according to purpose and use. Occupants have different thermal needs for the spaces they are in and the activities they do in those spaces. Educational buildings and classrooms for primary and secondary students have unique conditions and requirements for their occupants and, correspondingly, unique thermal needs [12,14,19]. Research from the past decade found that across Australia, schools have been built to meet only minimum building code requirements and that the educational facilities were not necessarily designed to provide comfortable, productive or healthy work environments for students and teachers [46].

Education facilities in Australia are designated as class 9b building types under the Australian National Construction Code (NCC). In Australia, there are no requirements regulating the optimum temperature required in classrooms and other educational buildings; however, there are PMV/ATC requirements [41]. For thermal comfort requirements of education facilities, the NCC section J uses the international standards for indoor thermal environments ASHRAE 55 [3]. For mechanically ventilated education buildings, the NCC requires ± 1.0 PMV “across not less than 95% of the floor area of all occupied zones for not less than 98% of the annual hours of operation of the building” [41]. For naturally ventilated buildings, the internal temperatures must be within 80% of the acceptability limit of ASHRAE Standard 55–2010 and ISO 7730 [38,39,41].

In addition to designing buildings to comply with the NCC, schools in each state in Australia have their own school design guidelines, which include a mention of thermal comfort or thermal performance of school buildings but little by way of specific guidelines or required outcomes for student thermal comfort [47–51]. Neither of Australia’s two territories produce a specific guide for school design. In recent years, the NSW Department of Education (NSW DoE) has supported investigations into thermal comfort in NSW classrooms [52,53], which have led to publications of specific guidelines for thermal comfort in NSW Education classrooms. The thermal guidelines are part of the larger NSW DoE Educational Facilities Standards and Guidelines (EFSG). The technical paper provides information on thermal comfort requirements. Non-government schools in NSW such as Catholic Schools and Independent Schools are required to follow the NSW Education Standards Authority, which includes requirement to follow the BCA (NCC) but has no specific requirements for temperature, PMV or other measures of thermal comfort in classrooms [54].

Academic research recognises that the development of classroom thermal comfort requirements based on ASHRAE’s data from the occupation of office buildings cannot be perfectly applied to classroom environments [12,14,55]. It is likewise acknowledged by the NSW DoE that “Australian building codes go some way in providing technical requirements for buildings, but they do not explain specific details relating to school

operations". To address this shortfall, the NSW Department of Education (NSW's School Infrastructure Design Framework: Sustainability) promotes Green Star as a best practice guide to "set a benchmark about the relevant building code, to reflect the actual use of facilities by schools" [56]. In addition to requiring building works for the NSW Department of Education to comply with the Deemed to Satisfy portion of section J of the NCC [57], the DoE encourages all classrooms to reach a higher standard of thermal comfort, and for any NSW Government development "with estimated total project costs over \$10 million and greater than 1000 m²", a 5-star Green Star must be achieved for Sydney, Wollongong or Newcastle metropolitan areas and 4 stars in the rest of the states [57] (p. 5). This translates to minimum Green Star thermal comfort PMV requirements for mechanically ventilated classrooms to be the same as the NCC for classrooms: where the PMV levels are between -1 and $+1$, for air-conditioned buildings and for naturally ventilated buildings, the internal temperatures must be within ATC 80% of Acceptability Limit 1 of ASHRAE Standard 55–2010. To reach two points in Green Star, two points are awarded in Green Star where the PMV levels are between -0.5 and $+0.5$ for new classrooms or the ATC internal temperatures are within 90% of Acceptability Limit 1 of ASHRAE Standard 55–2010. For existing classrooms, the PMV requirement is ± 0.7 for 95% of occupied hours [58].

Despite the adaptation of the thermal comfort requirements for Australian classrooms, a preliminary search of the literature shows uncertainty on the suitability of ASHRAE standards as a suitable way to assess thermal comfort of classrooms, considering that the complexity of educational buildings and the variety of learning activities may influence students' thermal comfort [12,14]. Thus, our second topic for the systemised literature search is to investigate the relationship between thermal comfort requirements and classroom building types.

2.6. Students

While significant ongoing research has been conducted on thermal comfort in domestic and commercial buildings, it has been noted that very few studies exist on thermal comfort in education buildings globally [6,9], and field investigations to understand thermal preferences of education building occupants are even less common [55]. Of the existing research on the effects of thermal comfort in educational buildings on student productivity and learning, international studies have found that the thermal environment is related to student success [9,59,60]. In many of these studies, temperature and ventilation were used to measure thermal comfort, whereas PMV or ATC acceptability indexes were rarely used to measure thermal comfort [59,60].

Related to children's reduced ability to learn at hotter temperatures, research highlights that children feel warmer and prefer cooler temperatures and a lower PMV [21,22]. Singh et al. reviewed 93 thermal comfort studies in classrooms and found that all studies agreed that children in classrooms preferred temperatures to be lower than that predicted for adults [9]. As the thermal preference and the metabolic rate [52] of children are different from adults, the PMV calculations and interpretations for children differ to those of adults. Because the value for thermal comfort in classrooms is based on adults and not children, researchers have highlighted this as an issue when determining thermal comfort in classrooms [9,10,19,55]. Furthermore, the ASHRE and ISO 7730 thermal comfort parameters are based on US and European adults, which adds to the disparity when children of diverse ethnicities are not included, as their preferences deviate from the "norm" [29]. Thermal conditions and preferences have been found to differ between children of different cultural backgrounds, even within the one nation [60].

In the Australian context, very few thermal comfort studies have been carried out in Australian schools [6]. A survey of Australian primary and secondary school children across

three distinct subtropical climate zones was conducted in a mixture of air-conditioned, evaporative cooled and naturally ventilated classrooms during the summer to investigate acceptable temperature ranges [52]. The studies coherently showed that the students' preferred temperature was around 22.5 °C [52] and 22.6 °C [6], generally cooler than expected for adults under similar conditions in both PMV and adaptive models of thermal comfort [19,52,53]. Of the research that directly discusses the suitability of ASHRAE in Australia, Kuiri has identified that Australian children need a lower temperature band than ASHRAE requires [7], and Tartarni et al. [61] note that it is problematic trying to follow ASHRAE and ISO guidelines when designing specific facilities for Australians who fall outside of the "Healthy Adult" category.

The significance of the relationship between thermal comfort and students, as highlighted by current research, brings it forward as a topic area for our systematised literature review.

2.7. Air Conditioning and Natural Ventilation

Air conditioning in classrooms has been recommended for better learning outcomes [60]. However, issues with air conditioning in classrooms have been raised by others [16,19,23], particularly when other solutions to improve thermal comfort, such as designing buildings for natural heating and cooling, do exist.

Air conditioning produces carbon emissions, as it significantly impacts energy consumption in buildings [6,7], as well as additional greenhouse gas emissions via refrigerant gasses [8]. The Australian National Construction Codes reflect the concern for energy consumption of air conditioning, with the NCC Section J allowing a maximum energy consumption of 43 kJ/m² h in thermally conditioned spaces in schools [41]. Regular classrooms in NSW are only required to be fitted with air conditioning when the mean max temp in January is over 33 °C at the location of the school. All modular classrooms (known as "demountables") in NSW are fitted with air conditioning regardless of their location [53]. Catholic and Independent Schools have their own policies and are not required to install air conditioning [23].

Research shows that as well as contributing to climate change, air conditioning does not provide good quality air for learning, with increased levels of CO₂ in classrooms due to insufficient air interchange [19,23], and naturally ventilated classrooms provide the lowest CO₂ levels of all classrooms [9]. De Dear et al. also suggest that exposure to natural climate cycles is beneficial for children, a view supported by Diaz-Lopez et al. [24] and more broadly by research into biophilia, which shows that a student's physical connection to nature improves their learning outcomes [62]. Simply opening up classrooms to the outdoor environment, however, does not automatically improve thermal conditions or student satisfaction [11].

Improving classroom design to maximise natural, passive solar design methods for thermal comfort, rather than relying on everyday use of air conditioning or other mechanical heating and cooling systems, has been encouraged by academic studies [10,20,24], whereby the "high energy consumption of air-conditioning is not necessarily required to achieve thermal comfort in many cases" [16] (p. 152). There is general agreement across the literature that there is a need for evidence-based research on ways to improve air quality and thermal comfort in Australian schools [6,63,64]. In Australia, NSW schools are embracing passive cooling in classroom design, including using improved insulation in classrooms [53]. The NSW's School Infrastructure Design Framework: Sustainability does include strategies for natural ventilation and encourages passive design principles to be applied for creating thermal comfort in schools [57]. Improved classroom design supports the NSW Department of Education's preference to use less air conditioning in all

classrooms while still achieving suitable thermal comfort [53]. The current research shows the need for greater understanding of the use of air conditioning in classrooms, and our systemised review includes this topic as a final research area.

3. Materials and Methods

3.1. Scope

To contribute to the local and global understanding of the suitability of ASHRAE thermal comfort standards for school classrooms in the climate type found in New South Wales, Australia, this research builds on the background literature review presented in the previous section with a structured, systematised review. The systematised review assesses international research to identify significant points of consideration in the complex inter-relationships of student learning, classrooms, climate, thermal comfort and air conditioning.

The systematised review identifies research gaps and demonstrates the current knowledge and insights within the field by collecting and analysing evidence from the literature that is available on the topic. To provide a comprehensive snapshot of academic research and the current state of the art for thermal comfort requirements for educational facilities, the preliminary review of the literature has identified the interlinked relationships between key areas that impact the situation of thermal comfort in classrooms, which can be summarised as climate zones, education buildings, students, thermal comfort and air conditioning (Figure 2). For this study, we include studies on primary, secondary and tertiary students who learn in government or private classrooms. The indoor classrooms can be of any type, single or multi-storey, permanent or relocatable/demountable. Our consideration of air conditioning means mechanical heating or cooling systems, such as heating, ventilation and cooling (HVAC) systems like air conditioners, chillers or evaporative coolers. If simple mechanisms like operable windows and fans are used, these are noted as natural ventilation.

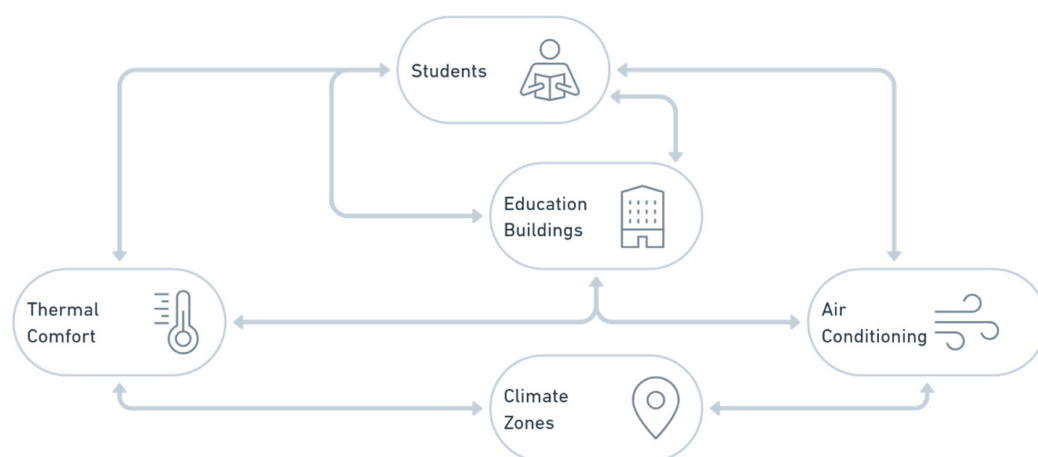


Figure 2. Inter-relationships between children, classrooms, thermal comfort, climate zones and air conditioning reviewed in this study.

3.2. The Systematised Literature Review Methodology

As defined by Grant and Booth, a systematised review uses the basic process of a systematic review without the high level specific and comprehensive methodology [65]. The systematised approach suits this present research, which requires a broader overview of the complexity of the four identified areas of significance. The outcomes of the systematised review can then be developed into an independent or a larger combined systematic review [66].

Following a background literature review of each factor, a systematised review (using comprehensive searching) was conducted for factors i–iv:

- (i) The relationship between thermal comfort requirements and local climate zones;
- (ii) The relationship between thermal comfort and educational building types (classrooms);
- (iii) The relationship between thermal comfort and students;
- (iv) The effect of air conditioning in educational buildings.

3.3. Systematised Literature Search Strategy

A literature search was undertaken to identify articles for each of the four focus areas in separate search processes. As this is a systematised review rather than a full systematic review, only one literature database was selected [67]. To select the database, we reviewed research into the key databases used in engineering and building. The two most suitable databases for energy efficiency and climate impacts of buildings have been identified by Cabeza et al. [68] to be Scopus and the Web of Science. Other research has found these two databases to have 78% full-citation overlap and that Scopus has a higher percentage of citations in the Engineering and Computer Science topic area (Scopus 61%; WoS 48%), which is the most relevant category for this research area [69]. Thus, Scopus alone was used, as it provides one of the most comprehensive databases, is most suited to the topic of thermal comfort in classrooms and has the highest citation rate for this research topic. Additionally, the Scopus database has advanced searching and filtering capabilities, which ensure the results match specific questions. Due to the interdisciplinary nature of the topic and the need to synthesise findings across these disciplines, using a single, suitable database ensured the review remained focused while producing an informed data set.

We used keywords both to select and refine the literature sources used in the systematised review. Keywords were used as search fields in Scopus along with abstract and title (TITLE-ABS-KEY) to conduct the preliminary literature search. After our assessment of the initial search results, we found the results included papers that were much broader than our initial inquiry; in particular, papers were included that did not focus on ASHRAE standards. So, we used post-query filtering using keywords, a method identified to ensure precise and relevant results [70], further filtering the papers via the post-query limit by the keyword feature of Scopus [71], taking advantage of keyword searching as a method to bring forward important papers to match the enquiry area [72,73].

Search terms were deliberately restrictive to maintain focus on this tight topic area. Following a pilot test, titles and abstracts were screened for assessment against the inclusion criteria. The papers were retrieved in full, and their citation details were imported into a digital spreadsheet. The observations of the three reviewers were then collated, and discussions between all reviewers were held, where any papers considered non-relevant were removed, and then a summary of each set of papers was written. For each research set, a unique set of search terms were used; then, the same exclusions were followed, and after, the initial search terms were run.

- (i) For the relationship between thermal comfort requirements and local climate zones, the search terms were (ASHRAE OR ISO) AND “climate zone”.
- (ii) For the relationship between thermal comfort requirements and building types (classrooms), the search terms were (ASHRAE OR ISO) AND Classroom*.
- (iii) For the relationship between thermal comfort requirements and students, the search terms were (ASHRAE OR ISO) AND student*.
- (iv) For the effect of air conditioning in classrooms, the search terms were (ASHRAE OR ISO) AND “air condition*” AND classroom*.

After each search query, we refined the results with 3 exclusions and 2 limitations. Any papers not in English and published before 2014 were excluded. Papers written in English were only used, as this is the one language in common for the authors. To mitigate this limitation, we maintained a broad geographic inclusion, and our climate zone criteria allowed the inclusion of relevant publications from a non-Western context. We used a decade boundary, as the research covers several topics that have had significant changes over the past decades. Thermal comfort standards such as ASHRAE and ISO, as well as building codes such as the NCC, over ten years old are considered outdated in the industry. The last decade has seen record-breaking global temperatures and more extreme weather patterns, so research since 2014 also reflects more current climate data, which is crucial for studies on thermal comfort and building performance.

This study aims to assess classroom thermal comfort in climate zones similar to NSW, based on information from nations that are likewise bound to international standards such as ASHRAE, but have different climates and cultures to the USA, the source of the standards. Concerns have been raised with the application of ASHRAE standards for the design and operation of buildings in an international context [17,18], and studies in thermal zones different to that of the USA are recommended [74] (Amoatey et al. 2023). Thus, as part of this study's broader strategy to focus our research on broader international perspectives to inform the parameters of localised thermal comfort benchmarks for NSW classrooms we excluded all papers from the USA. The Scopus keyword search was finally limited by the keywords "ASHRAE standards". After the initial enquiry, a final exclusion was placed on the papers that were not from the same climate zone as NSW Australia. To determine this, we identified the climate for each country in the filtered set of papers, using the Köppen–Geiger map. Any study that had at least one climate group that corresponded to one of NSW (arid and warm temperate) was retained. Some papers studied more than one country. If at least one of those countries met our climate zone requirements, that paper was included, and the information from the relevant nation was considered.

3.4. Data Extraction

A data extraction form was designed during the literature review process to include specific details about the concept, context, study methods and key findings relevant to the systematised review (Table 1). Data were extracted independently by the authors using the data enquiries that reflect the four identified factors contributing to thermal comfort in classrooms, as follows:

- Location and climate
 - Country of study: what country/countries were studied in the paper.
 - Köppen–Geiger climate classification of the county studied (climate only, not precipitation or temperature).
 - NSW climate zone match: if the climate zone of the studied country matches at least one of the climate zones of NSW (warm temperate and/or arid).
- Thermal Comfort
 - Measure of thermal comfort: which standard thermal comfort (and air quality) assessments are used; see legend for abbreviations.
 - Thermal comfort standard: which known standard mentioned in the paper; see legend for abbreviations.
- Education building
 - The building type: primary, secondary or tertiary classroom or other building type, as described.

- The heating/cooling system is used in the building, whether mechanical, such as air conditioning, or natural ventilation, such as natural thermal conditions and air movement but also including fans.
- Students
 - If the study found student preferences for thermal comfort, the values are recorded.

Table 1. The data extraction form used for all papers.

Reference	Climate Zone			Thermal Comfort		Buildings		Students
	Country of study	Köppen–Geiger climate classification	NSW climate zone match	Thermal comfort standard	Thermal comfort measure	Building type(s)	Heating/cooling system	Student thermal preference

The data extraction and analysis were conducted through a collaborative and iterative process involving all authors as reviewers. The reviewers completed their data extraction forms independently using the structured data extraction form developed during the literature review process, discussing the inclusion or detail of data when necessary. The resulting data sets were then discussed by all three reviewers to ensure consensus and consistency. The findings were synthesised narratively, using multi-dimensional thematic triangulation across the four thematic areas. The data are presented in tabular form, accompanied by a narrative summary that describes how the findings relate to the four factors of this study.

4. Findings

The search process for the four inquiry areas initially found 1546 papers. After refining and screening the literature using the approach described in the method section, the search found 31 publications over the four topic areas (Table 2).

Table 2. Number of papers found from search strategies i–iv.

Research Inquiry	Initial Number of Papers	Final Number of Papers After Screening	Number of Papers Overlapping in Inquiries (i–iv)	Number of Unique Papers	Number in Table	Total Number of Papers
 i. Climate zone	322	15	1	14	Table A = 15	31
 ii. Classroom building types	236	18	13	4		
 iii. Students	915	10	9	1	Table B = 17	
 iv. Air conditioning	73	5	6	0		

Unsurprisingly, many of the same papers were selected by the related topic searching, so there were overlapping findings for some of the research inquiries. The search on climate zone (i) returned only one paper that overlapped with other inquiries, while the other three

search areas had several of the same results. To present the results clearly, Table 3 provides the data extraction results for search i (climate zone), while Table 4 combines the results for the inquiries ii–iv (classrooms, students and air conditioning), including clarification on which search was connected to the paper. The data extraction tables are interpreted in the findings, presented by topic area.

Table 3. Findings from search strategy i (climate zone).

Reference	Country of Study	Climate Zone	NSW Climate Zone Match	Thermal Comfort		Buildings		Students
		Köppen–Geiger Climate Classification		Thermal Comfort Standard	Thermal Comfort Measure	Building Type(s)	Heating/Cooling System	Student Thermal Preference
Ascanio-Villabona et al., 2021 [75]	Colombia	Cfb warm temperate	yes	ASHRAE 55	PMV	Residential	MECH	No
Bhatnagar et al., 2018 [76]	India	Am, Aw, BSh, Csa tropical, arid, warm temperate	yes	None	None	Commercial	MECH	No
Carlucci et al., 2018 [77]	Amsterdam, Beijing, Shanghai, Palermo and San Francisco	Cfb, Dwa, Csa, Csb, Cfa warm temperate, snow	yes	EN 16798, ASHRAE 55, GB/T 50785, ISSO 74	ATC	Not specified	NV	No
Crosby et al., 2019 [78]	South Asia	Cwa, Am warm temperate, tropical	yes	None	None	Commercial	MECH	No
Defo et al., 2019 [79]	Canada	BSk, Cfb, Dfb arid, warm temperate, snow	yes	None	None	Residential, Commercial	NV	No
Efeoma et al., 2016 [80]	Nigeria	BSh, Aw, Am arid, tropical	yes	ASHRAE55, EN 15251	ATC	Commercial	NV	No
Eldin & Badawi 2014 [81]	Middle East	BWh arid	yes	None	None	Industrial	MECH	No
Gallardo et al., 2025 [82]	Canada	BSk, Csa, Cfb arid, warm temperate	yes	None	None	Commercial	NV	No
Hong et al., 2025 [83]	South Korea	Cwa, Dwa warm temperate, snow	yes	None	None	Commercial	MECH	No
Kim et al., 2021 [84]	Japan and South Korea	Cfa, Dfa, Cwa, Dwa warm temperate, snow	yes	None	None	Not specified	MECH	No
Kumar et al., 2018 [85]	India	Am, Aw, BSh, Csa tropical, arid, warm temperate	yes	ASHRAE 55	Thermal discomfort time	Commercial	NV	No
Parmaksiz et al., 2024 [86] Also found in search iii	Turkey	Bsh, Csa, Csb, Cwa, Dwd, Dfb arid, warm temperate, snow	yes	ASHRAE 55, ISO 7730	PMV, PPD	Primary and secondary classrooms	MECH and NV	No
Sánchez-García et al., 2023 [87]	Japan	Cfa, Dfb warm temperate, snow	yes	ASHRAE 55	Japanese version of ATC	Residential	MECH and NV	No
Sánchez-García et al., 2024 [88]	Brazil	Af, Am, Aw, Cfa warm temperate, tropical	yes	ASHRAE 55	ATC	Residential	MECH and NV	No
Wang et al., 2023 [89]	China	BSk, Cfa, Cfb, Cwa Dwa, Dwba arid, warm temperate, snow	yes	None	None	Not specified	MECH	No

Table 4. Findings from search strategies ii, iii and iv (classrooms, students and air conditioning).

Reference and Search Strategy (ii–iv)	Climate Zone		Thermal Comfort			Buildings		Students
	Country of Study	Köppen–Geiger Climate	NSW Climate Zone Match	Thermal Comfort Standard	Thermal Comfort Measure	Building Type(s)	Heating/Cooling System	Student Thermal Preference Values
Abuelnuor et al., 2021 [90] (ii) (iii)	Sudan	BWh, BSh Arid	Yes	ASHRAE 55	PMV, ATC, air speed, RH	Primary classroom	MECH	No
Ali and Al-Hashlamun, 2019 [91] (ii)	Jordan	BWh, BWk, Bsk, Csa arid, warm temperate	Yes	ASHRAE 55, DB, ISO 7730	ATC	Primary and secondary classrooms	NV	24.0 °C–27.5 °C
Amoatey et al., 2023 [74] (ii) (iii)	Oman	Bwh arid	Yes	ASHRAE 55, WHO, EN16798, EN 12464	PMV, PPD, T, RH	Secondary classroom	MECH and NV	No
Asif et al. 2018 [92] (ii) (iv)	Pakistan	BWh, BSh arid	Yes	ASHRAE 55, ASHRAE 62.1	T, RH, CO ₂	University classroom	MECH and NV	No
Asif & Zeeshan, 2020 [93] (ii)	Pakistan	BWh, BSh arid	Yes	-	CO ₂ , T, RH	Primary classroom	MECH	No
Bajc et al., 2016 [94] (ii) (iv)	Greece and Serbia	Greece: Csa, Csb, Cfb, Cfa warm temperate Serbia: Cfb warm temperate	Yes	EN 15251, ASHRAE 55 and ASHRAE 62.1, ISO 7730	T, RH, CO ₂	University offices and classroom	MECH and NV	No
Bajc et al., 2019 [95] (ii) (iii)	Serbia	Cfb warm temperate	Yes	ISO 7730 ASHRAE 55, ISO 10551	PMV, PPD, CO ₂	University classroom	MECH	No
Fang et al., 2018 [96] (ii) (iii) (iv)	Hong Kong	Cwa warm temperate	Yes	ASHRAE 55, ISO 7730	UCB, PMV, (M)TSV, T_{op}	University classroom	MECH	Neutral and preferred temperature approx. 24 °C; suggested set point for AC temp = 26 °C
Hadziahmetovic et al., 2022 [97] (ii)	Sarajevo	Cfb, Dfb warm temperate, snow	Yes	EN 15251, EN 16798, EN 13779, ASHRAE 62.1	PMV, PPD, CO ₂	University classroom	MECH	No
Korsavi et al., 2017 [98] (ii) (iii)	Iran	BWh, BWh, BSk, Csa arid and warm temperate	Yes	ASHRAE 55	PMV, TSV	Primary and secondary classrooms	NV	Neutral temperatures 18.7–26.4 °C
Korsavi et al., 2020 [99] (ii)	UK	Cfb, Cfc warm temperate	Yes	ASHRAE 62, EN 13779	Air speed, air change rates, ventilation rates	Primary classroom	NV	No
Kuru & Calis, 2018 [100] (ii) (iii)	Turkey	Csa, Csb, CWa, Dwd, Dfb warm temperate, snow	Yes	ASHRAE 62.1	PMV, CO ₂	University classroom	MECH	No
Lee et al. 2014 [101] (ii) (iii) (iv)	Taiwan	Cfa, Cfb, Cwa, Cwb warm temperate	Yes	ASHRAE 55	PMV, T, RH	University classroom	MECH and NV	Maximum temperatures: 27.3 °C (NV) 26.3 °C (AC)
Li et al., 2024 [102] (iii)	China	BSk, Cfa, Cfb, Cwa Dwa, Dw b arid, warm temperate, snow	Yes	ASHRAE 62.1, ASHRAE 241	PMV, T, solar radiation	Primary, secondary and university classrooms	MECH	No
Parmaksiz et al., 2024 [86] (i) (ii)	Turkey	Csa, Csb, CWa, Dwd, Dfb warm temperate, snow	Yes	ASHRAE 55 ISO 7730	PMV, PPD	Primary and secondary classrooms	MECH and NV	No
Singh et al., 2018 [103] (ii) (iii)	India	Am, Aw, BSh, Csa tropical, arid, warm temperate	Yes	ASHRAE 55	T, RH, air speed, indoor air temperature, air velocity	University classroom	NV	Comfort zone 23–32 °C, mean temperature 29.8 °C
Zaki et al., 2017 [104] (ii) (iii) (iv)	Japan and Malaysia	Japan: Cfa, Dfb warm temperate/snow	Yes (Japan)	EN, ASHRAE, CIBSE	TSV, PMV, PPD, RH, T, air speed velocity	University classroom	MECH and NV	Japan: 25.1 °C (NV) 26.2 °C (AC)

4.1. Systematised Search Results

Tables 3 and 4 Key:

Köppen–Geiger Climate classification: See definitions in Kottek et al. [25].

Thermal comfort measure: ATC—Adaptive Thermal Comfort; CO₂—carbon dioxide levels; PMV—Predictive Mean Vote index; PPD—Predicted Percentage Dissatisfied; RH—relative humidity; SET—Standard Effective Temperature; T—temperature; T_{op}—operative temperature; TSV—Thermal Sensation Vote; UCB—University of California, Berkeley, model.

Heating/Cooling system: MECH—mechanical air conditioning; NV—natural ventilation (incl. fans); Mixed—mixed mode.

4.2. Systematised Search Findings

Examining all of the papers found in the combined searches (i–iv), the nations studied are Brazil [n = 1], Canada [n = 2], China [n = 3], Colombia [n = 2], Greece [n = 1], Hong Kong [n = 1], India [n = 3], Iran [n = 1], Italy [n = 1], Japan [n = 3], Jordan [n = 1], Middle East region [n = 1], the Netherlands [n = 1], Nigeria [n = 1], Oman [n = 1], Pakistan [n = 2], Sarajevo [n = 1], Serbia [n = 2], South Asia region [n = 1], South Korea [n = 2], Sudan [n = 1], Taiwan [n = 1], Turkey [n = 3] and the UK [n = 1]. Using the Köppen–Geiger climate classification [25], the climate zones of these nations mostly include warm temperate [n = 25] and arid [n = 15]. University classrooms were the main location of study in this set of papers [n = 10]; eight studies included primary school classrooms, and five papers looked at secondary school classrooms.

Predictive Mean Vote (PMV) [n = 12] was the most popular approach to assess thermal comfort and indoor air quality, followed by temperature assessment [n = 9], humidity levels [n = 8], Predicted Percentage Dissatisfied (PPD) [n = 6], Adaptive Thermal Comfort, ATC [n = 6], CO₂ levels [n = 6], air speed/velocity [n = 4], Thermal Sensation Vote (TSV) [n = 3], Berkeley Comfort Model (UCB) [n = 1] and solar radiation [n = 1]. Most papers included at least one of the ASHRAE standards for thermal comfort, indoor air quality or clean airflow (ASHRAE 55, 62.1 and 241) [n = 23]. Additionally, European standards for temperature, light and humidity were used (EN 16798, 12464, 13,779 and 15251) [n = 8], as were the International Organization for Standardization (ISO) thermal comfort standards (7730 and 10551) [n = 6] and the World Health Organization guidelines (WHO) [n = 1].

Of all the papers studied, mechanical cooling (MECH) is the most common approach [n = 14]. Natural ventilation (NV) was applied in nine environments. Likewise, nine studies mentioned a mixed-mode strategy, with a combination of mechanical and natural ventilation. Of the papers that analysed education buildings, seven looked at buildings with only mechanical heating or cooling, seven had a mix of both mechanical and natural systems (including fans), and four had natural heating cooling systems only.

4.3. Findings from Search i: The Relationship Between Thermal Comfort Requirements and Local Climate Zones

This section provides a summary of the papers found on thermal comfort requirements and local climate zones using search strategy i (Figure 3). Table 5 provides a summary of the frequency of findings in the papers for this search.

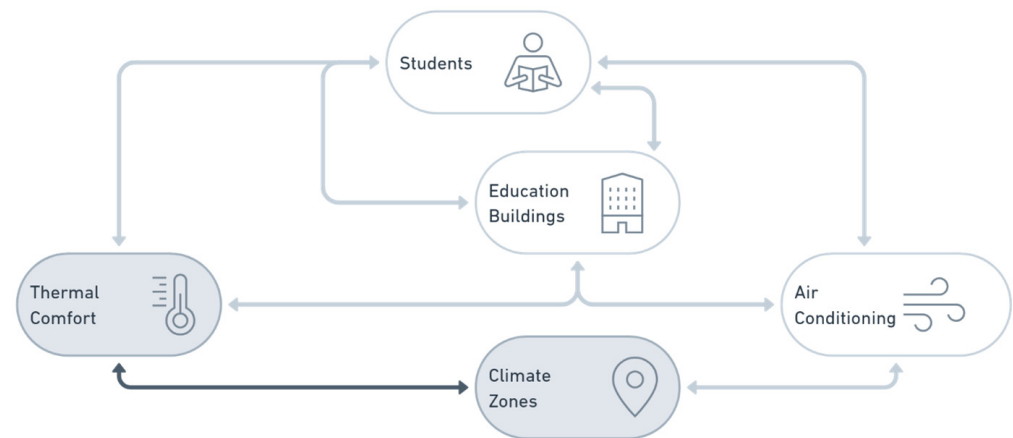


Figure 3. Relationship between thermal comfort and climate zones in the research context.

Table 5. Number of papers that include information on the climate zone, thermal comfort, buildings and students for search i.

Climate Zone						
Arid	Warm temperate		Tropical	Snow		
8	13		5	7		
Thermal Comfort						
ISO standards	ASHRAE standards		EN standards	Other standard		
2	7		2	1		
Temperature	Humidity	Air speed	PMV	PPD	ATC	Other
-	-	-	2	1	4	1
Buildings—classroom type			Buildings—heating and cooling system			
Primary	Secondary	Tertiary	Mechanical	Natural	Both	
1	1	-	7	5	3	
Students						
Number of papers providing student thermal preference values						

The majority of the research from this set (which did not include a search term for classrooms or students) has been conducted on residential and office buildings, with a growing emphasis on institutional and commercial buildings [80]. Only one study [85] has examined primary and high school classrooms in a semi-arid climate, indicating that educational buildings are still underexplored.

The papers mostly apply typical international standards and measurement models. ASHRAE 55 is the most frequently cited standard in this set [74,79,84–87], frequently accompanied by ISO 7730 [85] or national standards like EN 15,251 [79]. While some studies used static models like PMV and PPD [85] or qualitative methods like “thermal discomfort time” [84], the thermal behaviour of buildings was demonstrated through the Fanger method, which was employed to determine the balance of energy loading and thermal comfort in accordance with the ASHRAE 55 standard [74]. However, many studies failed to report any thermal comfort model or standard [76,78–80,88,105]. Overall, the range of approaches, or unreported methodologies, shows a lack of standard consistency in the methodology throughout the field.

Only a few papers used comfort models that were adaptable to different places, like Japan and Brazil [87,88]. For example, Sánchez-García et al. [88] used a local Brazilian adaptive model based on the prevailing mean outdoor temperature (PMOT) to identify preferred thermal comfort ranges with occupant data.

Most of the studies in this set lack user-centred or perception-based research. The majority emphasised technical measures or simulated comfort environments without evaluating the lived experiences of occupants. Only Efeoma et al. [80] and Sánchez-García et al. [87] explicitly included occupant feedback in comfort models, highlighting a broad difficulty in matching thermal comfort theory with practical applications. This disconnection limits the ability of existing research to guide real occupant-centred design solutions, particularly in educational buildings.

Although international thermal comfort standards, including ISO 7730 [39] and ASHRAE 55 [38], have been widely adopted, this review emphasises their limited accuracy when applied generically across worldwide contexts. The findings from these papers indicate that international standards may not adequately account for localised climatic conditions, cultural expectations and occupant behaviours, including in educational buildings [84]. Consequently, it is essential to establish localised thermal comfort standards that are specifically designed to reflect the specific climatic and social conditions of a unique location.

Overall, this review emphasises the importance of more detailed, adaptive, and user-oriented thermal comfort research covering various worldwide environments. While existing standards like ASHRAE 55 provide a helpful basis, future research should focus on context-specific modelling, hybrid cooling systems and occupant perception data, particularly for educational and low-energy buildings. For the NSW climate zone, developing a regional thermal comfort standard based on local climate and occupant demands, particularly students, is a key improvement in indoor environmental quality practice.

4.4. Findings from Search ii: The Relationship Between Thermal Comfort and Classroom Building Type

This section provides a summary of the papers found on thermal comfort and classroom building type using search strategy ii (Figure 4). Table 6 provides a summary of the frequency of findings in the papers for this search.

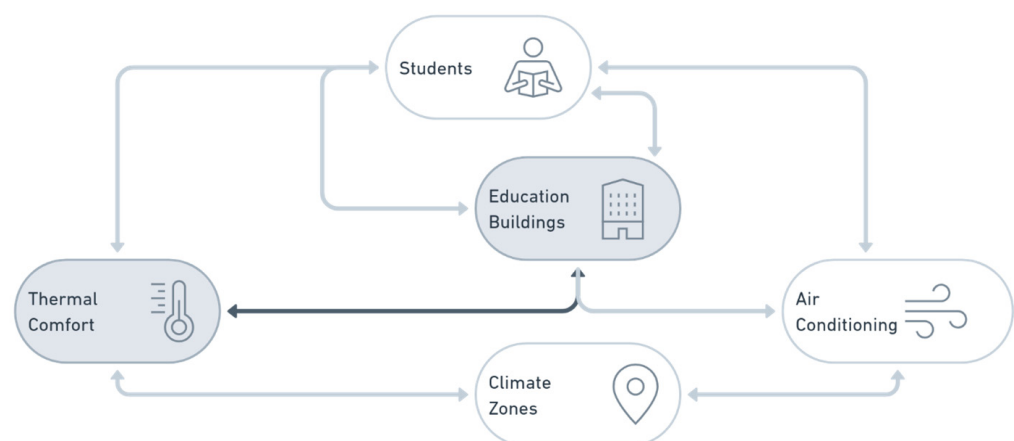


Figure 4. Relationship between thermal comfort and classroom building type.

Table 6. Number of papers that include information on the climate zone, thermal comfort, buildings and students for search ii.

Climate Zone						
Arid	Warm temperate		Tropical	Snow		
7	12		1	4		
Thermal Comfort						
ISO standards	ASHRAE standards		EN standards	Other standard		
5	15		5	3		
Temperature	Humidity	Air speed	PMV	PPD	ATC	Other
7	8	4	10	5	1	11
Buildings—classroom type			Buildings—heating and cooling system			
Primary	Secondary	Tertiary	Mechanical	Natural	Both	
6	4	9	6	4	6	
Students						
Number of papers providing student thermal preference values						
6						

While ASHRAE standards for classrooms are based on office spaces, authors from this set of papers on thermal comfort and classrooms identify that the classroom building type differs from an office space and that the classroom has distinctive features and design complexities, such as densely packed occupants who spend a lot of their daily time in classrooms [73,98]. Students are unique building users, as they have little control over their thermal setting, with no authority to adjust classroom heating or cooling and often being restricted to wearing a school uniform [94,95,97,102,103].

In the wide range of locations and building types studied in this set of papers, some of the studies on primary and secondary classrooms report temperature and relative humidity values exceeding the requirements during a significant portion of classroom occupancy periods, in all seasons, despite the presence of mechanical heating and cooling [89,92]. Poor thermal conditions that did not meet ASHRAE Standard 55 were attributed to the high number of students and the use of unsuitable building materials [89]. In one study conducted in different classroom buildings in the same city, some classrooms met thermal conditions, while others did not, having higher operating temperatures. The different thermal conditions were attributed to the different building designs and window numbers [73]. Additionally, the thermal comfort parameters were found to be influenced by outdoor climatic conditions and the building orientation of education buildings [91]. Improving classroom design to provide better thermal conditions and air quality was raised by several authors [73,93], with proposals that solar-based orientation and insulation of the classrooms would improve thermal comfort, as well as the consideration of number of students in a classroom [91]. Evidence on improving classroom design was provided by Singh et al. [103], who showed that the use of ceiling fans during the summer can enhance thermal comfort in classrooms. Zaki et al. [104] also suggest that the ability of students to adjust their conditions reduces the need for air conditioning, as they found university students felt more thermally comfortable because they could modify their clothing, consume beverages and even open doors and windows. These adaptations, however, are unlikely to be available for many primary or secondary school students.

Despite the number of papers noting the thermal conditions in primary and secondary classrooms being outside standard requirements, other studies found that primary classrooms conditions did fall into acceptable temperature ranges [90], often using mechanical approaches to achieve this. The papers noted that not all classrooms used consistent approaches to maintain thermal comfort and were instead flexible in their cooling and heating strategies. For example, Asif and Zeeshan note, in their study on primary school classrooms in Pakistan, that during the summer, split-type air-conditioning (AC) units were switched on during occupancy hours, while during the winter, portable fan heaters served the heating purpose [92].

In most university classroom settings, the indoor air temperature was found to mostly remain within permitted limits of thermal standards regardless of climate zones [95,96]. However, it is important to note that these values represent the recommended indoor air temperature for educational institutions according to the thermal standards and may not necessarily reflect students' actual thermal preferences. It is worthwhile to note that Bajc et al. [93] found that, on average, the indoor thermal environment in new university classrooms was more satisfactory than in old ones, indicating the higher thermal efficiency of the envelope of the new classrooms.

Across all classroom types, it was noted that many school buildings fail to provide adequate ventilation according to EN 13,779 and ASHRAE standards [97]. A comparison with ASHRAE standards by Asif and Zeeshan [92] showed indoor CO₂ levels exceeding acceptable limits during classrooms occupancy hours. Kuru & Calis [100] reported that the CO₂ concentration measurements exceeded the permissible concentration value of 1000 ppm stated by the ASHRAE 62.1 Standard and WHO in university classrooms during the summer season in India. They also suggested that there is a strong positive correlation between PMV values and CO₂ concentrations. In other words, when there is an increase in the PMV value, the CO₂ concentration also increases, and vice versa. Similar findings have been observed in Parmaksiz et al.'s study [86], indicating that CO₂ levels frequently exceed recommended limits, even when mechanical ventilation systems are in use. These results emphasise the urgent need for upgrading ventilation systems in schools and improving indoor air quality.

Overall, the type of classroom building, including its design, materials and ventilation methods, plays a crucial role in determining thermal comfort and air quality. The literature shows that thermal conditions vary significantly across different types of classrooms. Primary classrooms, especially in public schools, often face poor thermal conditions due to high occupancy and inadequate insulation. Secondary school students in government schools report better comfort than those in private schools, likely due to better design features. University classrooms generally maintain acceptable thermal conditions, with newer buildings performing better than older ones. These findings underscore the importance of considering classroom type and building design to enhance thermal conditions in classrooms.

4.5. Findings from Search iii: The Relationship Between Thermal Comfort and Students

This section provides a summary of the papers found on thermal comfort and students using search strategy iii (Figure 5). Table 7 provides a summary of the frequency of findings in the papers for this search.

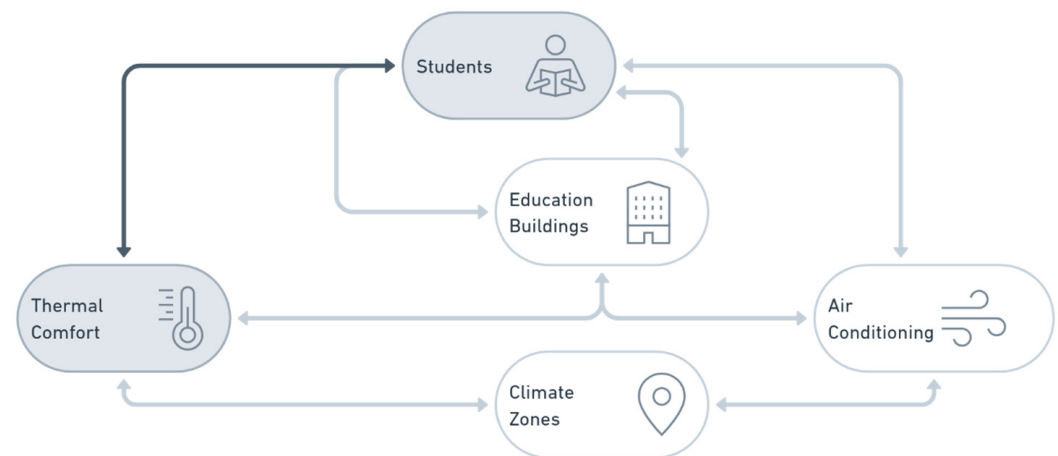


Figure 5. Relationship between thermal comfort and students.

Table 7. Number of papers that include information on the climate zone, thermal comfort, buildings and students for search iii.

Climate Zone						
Arid	Warm temperate		Tropical	Snow		
5	8		1	2		
Thermal Comfort						
ISO standards	ASHRAE standards		EN standards	Other standard		
2	10		2	1		
Temperature	Humidity	Air speed	PMV	PPD	ATC	Other
6	5	3	9	3	1	5
Buildings—classroom type			Buildings—heating and cooling system			
Primary	Secondary	Tertiary	Mechanical	Natural	Both	
3	2	7	5	2	3	
Students						
Number of papers providing student thermal preference values						
5						

This set of papers focuses on students in relation to thermal preference. Except for one [101], all the papers found from the search strategy for this section are also captured by search ii (classroom and thermal comfort) and/or search iv (air conditioning and students). When considering the importance of thermal comfort to students, particularly in their unique climate zone, the papers emphasised the importance of health and wellbeing of students in classrooms [73,94,101,102]. The authors also highlighted other academic research that demonstrates the effects of thermal comfort (and indoor environment including air quality) on student learning [73,89,102], performance and productivity [94]. Air quality for students was raised in several papers, particularly the CO₂ loads [73,99,101].

Regarding student preference for set thermal conditions, many papers studying student preferences found some level of discomfort in the classroom [73,94]. The study by Lee et al. in Taiwan [101] found that the maximum acceptable thermal temperature of students in naturally ventilated classrooms was 27.3 °C, and in air-conditioned classrooms, 26.3 °C, while in Japan, Zaki found the mean comfort for students in naturally ventilated classrooms to be 25.1 °C and 26.2 °C in air-conditioned classrooms [104]. Fang

et al. found the comfort range temperature for university students in Hong Kong to be 21.65–26.75 °C, with a neutral operative temp of 24.14 °C [95]. Singh et al. found students in India to have a comfort zone of 23–32 °C, with a mean indoor comfort temperature of 29.8 °C [102]. Korsavi et al. found for Iran that while the Thermal Sensation Vote (TSV) acceptable range was 18.7–26.4 °C, the PMV neutral range was 20.9–24.9 °C [97]. Uniquely, Zaki et al. also considered the different thermal preferences for female and male students and found them to be different [103].

The papers note that the climate zone affects the thermal preference of occupants [95,100,103]. As the studies were from arid and warm temperate climates, it was noted that the PMV model used by ASHRAE was designed for cooler climates and did not correlate to warmer climates [100]. Conversely, others in warm temperate climates [103] propose that ASHRAE can be used in hotter climates, a claim supported by the literature review of Fang et al. [96]; however, ultimately, Fang et al. propose that “to evaluate indoor thermal environment correctly, the comfort ranges of each climate zone needs to be specifically modified” [95].

Only a few papers found that thermal conditions for students in the classrooms did fall within ASHRAE standards [103], and Li et al. reported difficulty to achieve the standards, even with mechanical assistance [101]. Most papers noted that the thermal conditions of their classrooms did not all fall within ASHRAE standard requirements for thermal comfort [73,89,95,97,102]. Of these papers, some found that students were uncomfortable in non-ASHRAE-compliant classrooms, leading some authors to suggest that the ASHRAE range may apply for their location [73] or, perhaps, with slight modification [95]. However, other studies found that despite students’ thermal preferences falling outside ASHRAE requirements, the students were still comfortable [89,100,102]. These slightly confusing findings can be considered in the context of different local climates [100]; however, Korsavi et al. found that the PMV approach (used in ASHRAE) “overestimates children’s thermal sensation at high temperatures and underestimates it at low temperatures” [97] (p. 1169).

4.6. Findings from Search iv: The Relationship Between Air Conditioning and Classrooms

This section provides a summary of the papers found on air conditioning and classrooms using search strategy iv (Figure 6). Table 8 provides a summary of the frequency of findings in the papers for this search.

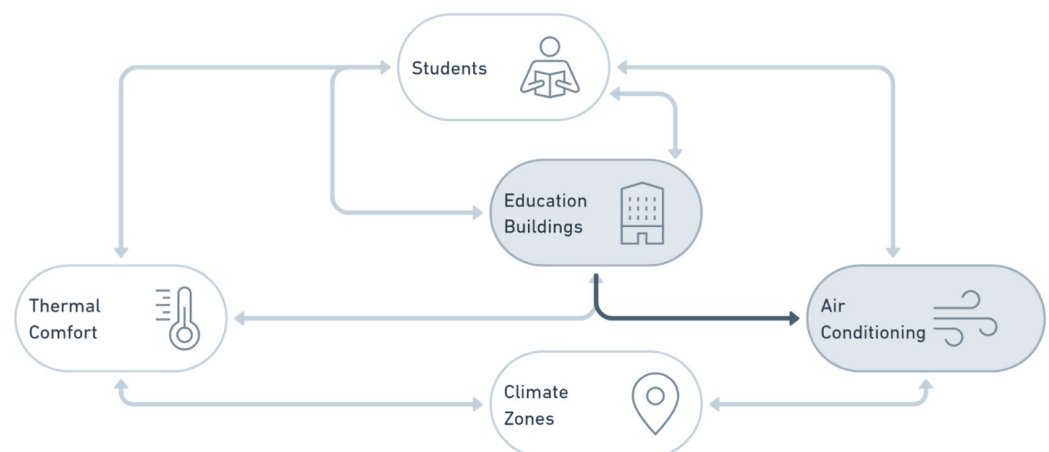


Figure 6. Relationship between air conditioning and classrooms.

Table 8. Number of papers that include information on the climate zone, thermal comfort, buildings and students for search iv.

Climate Zone						
Arid	Warm temperate		Tropical	Snow		
Thermal Comfort						
ISO standards	ASHRAE standards		EN standards	Other standard		
Temperature	Humidity	Air speed	PMV	PPD	ATC	Other
Buildings—classroom type			Buildings—heating and cooling system			
Primary	Secondary	Tertiary	Mechanical	Natural	Both	
Students						
Number of papers providing student thermal preference values						

Compared to the other systemised search result sets in this study, there was a lower number of papers returned [$n = 5$], and no papers published after 2018. All of the papers were concerned with university thermal comfort; one of those included a university office [93], and all discussed mechanical air conditioning, as well as some type of natural ventilation. The papers agree (or take it for granted) that air conditioning is commonly required for thermal comfort in classrooms [95,100]; however, it is also noted that mechanical air conditioning is often a necessary evil, required due to poor classroom design [91,103]. Asif et al. also noted that mechanical air conditioning can also help with air quality, but often, it does not [92].

The papers raised issues with air conditioning in classrooms. The results from Lee et al.'s study found that in air-conditioned classrooms, students develop a lesser ability to cope with higher temperatures [100]. On the other end of the temperature spectrum, students found air-conditioned classrooms set to ASHRAE standards to be too cool [103]. The importance of good air quality was covered by Bajc et al. [94], and Asif et al. [92] were concerned that other air pollutants were not measured but likely to be present in conjunction with elevated CO₂ levels in air-conditioned classrooms.

The papers noted that mechanical air conditioning consumes significant energy. Many papers proposed that a higher temperature should be set on air conditioners to reduce energy consumption [95,100,103], for example, by disregarding the ASHRAE 55 standard, adjusting the thermal comfort to students' needs, supplementing with natural ventilation [100] or setting temperatures to the upper limit of student preference [95].

Alternatives to mechanical air conditioning were suggested by most authors. Examples of replacing or supplementing air conditioning included ceiling fans and natural ventilation [100]. However, other research found that decentralised systems performed poorly for air quality in their study [91], and Bajic et al. note that it is difficult to moderate CO₂ buildup in naturally ventilated buildings without good air flow design [93].

5. Discussion and Recommendations

This review highlights the complexity and variability of thermal comfort requirements across diverse climate zones and building types, with a particular emphasis on educational environments. It demonstrates that while international standards such as ASHRAE and ISO may be met in classroom settings, their generalised approach does not always reflect the unique thermal comfort needs of local climatic conditions, user preferences and occupant behaviour, particularly in school environments.

Countries such as Australia have distinctive climatic characteristics, and classrooms represent a specialised building type that differs significantly from office spaces, which are the basis for most thermal comfort standards. Notably, the thermal preferences of students tend to be lower than those predicted by the Predicted Mean Vote (PMV) model outlined in international standards. While mechanical air conditioning might appear to offer a straightforward solution, in the context of the Sustainable Development Goals and environmental responsibility, alternative approaches such as retrofitting classrooms to enhance passive thermal comfort are recommended by several studies.

From this study, actionable insights for policymakers, architects and educators can be derived, with emphasis on the need for sustainable classroom designs and localised thermal comfort standards. Several promising strategies for improving thermal comfort without increasing energy dependence have been identified. Enhanced building design plays a key role in achieving optimal ventilation and maintaining comfortable indoor temperatures. Factors such as classroom orientation, insulation and the number of occupants have been highlighted as crucial elements to consider in improving thermal conditions. Additionally, allowing occupants the flexibility to adjust their environment, such as through clothing or ventilation, has been found to increase comfort. However, this level of control is more challenging to implement in primary and secondary school settings, where the flexibility seen in higher education environments is less feasible.

However, this review also demonstrates that the design of classrooms to achieve optimal thermal conditions for students requires an understanding of local thermal comfort preferences and, thus, appropriate thermal comfort standards. It is suggested that policymakers collate and conduct further research into thermal preferences of students in classrooms in their own unique climate zones and set thermal comfort standards accordingly.

Further research is needed to develop context-specific metrics that reflect the unique physiological and behavioural characteristics of students, as well as the climatic variability and educational priorities of different regions. Future research is recommended, such as field studies on students' adaptive responses to thermal conditions and the impact of passive cooling strategies. Incorporating user-centred data—particularly from students—into thermal comfort assessments can bridge the gap between compliance with standards and real occupant satisfaction.

Empirical studies are also needed to capture the seasonal thermal behaviour of educational buildings and students' adaptive responses. Comparative analysis of findings from NSW classroom studies on student thermal preference with findings from other regions or climate zones, along with their correlation with ASHRAE standards, would contribute to this research in the Australian context. Special attention should be given to mixed-mode and passive design strategies, which remain underexplored despite their strong sustainability benefits.

By highlighting the need for thermally comfortable and energy-efficient learning environments, these findings have broader implications for achieving the Sustainable Development Goals, particularly those related to quality education (SDG 4), sustainable cities and communities (SDG 11) and climate action (SDG 13). Policymakers are encouraged to revise national and state building codes—such as the NCC and NSW EFSG—to incorporate localised thermal comfort standards that reflect student's physiological needs and regional climate conditions, as supported by the studies found in this systematised review.

6. Conclusions

Across the reviewed literature, several key concerns were identified regarding the suitability of applying office-based thermal comfort standards to classroom environments. Classrooms typically impose restrictions on clothing flexibility, which means that students experience thermal conditions differently than occupants in office settings. In addition, clothing expectations and practices vary across countries, further complicating the application of generalised standards.

It was consistently observed that students tend to prefer cooler indoor temperatures than those set out in existing standards. While many student responses fall within the acceptable range defined by common standards, they do not consistently meet the 90% acceptability threshold. More critically, the Predicted Mean Vote (PMV) model often fails to reflect the actual thermal perception of students, suggesting a misalignment between the metric and lived experience in classroom settings.

Thermal preferences are also shaped by climate zones, with notable differences between those in cooler versus hotter or tropical regions. The PMV model, originally developed for temperate climates, has been found to correlate poorly with thermal comfort in warmer environments. While some evidence suggests that standards like ASHRAE may be adaptable to various climates, it is clear that comfort ranges must be locally adjusted to reflect regional climatic realities. The literature also highlights that schools adopt diverse and adaptive strategies to manage indoor temperatures. These include using air conditioning during the summer and portable heaters during the winter, depending on the available infrastructure and seasonal needs. This pragmatic approach reflects the lack of a consistent framework or benchmark for thermal comfort in educational buildings and underscores the need for standards specifically tailored to classroom contexts.

Our thematic synthesis across four key areas reveals the following challenges and considerations:

1. Climate zones: Local climates significantly influence thermal comfort, yet current regulatory standards do not adequately consider shifting climate patterns in a warming world.
2. Classroom design: No clear benchmark currently exists for evaluating thermal comfort in educational buildings. The applicability of ASHRAE standards remains uncertain.
3. Student physiology: Children have different metabolic rates than adults, and studies indicate they often prefer lower temperatures, which calls into question the validity of applying adult-oriented PMV models in classroom settings.
4. Air conditioning vs. passive design: While air conditioning supports comfort, passive design approaches—such as improved orientation, insulation and ventilation—are more sustainable and beneficial for indoor air quality.

While the need for thermal comfort in classrooms is clearly established, this review raises significant concerns about the suitability of PMV as a measure for educational settings. If we aim to improve indoor conditions based on measurable criteria, those measurements must be appropriate to the context. In the case of children in classrooms, there is insufficient evidence to confirm whether PMV—as defined by current standards such as the NCC or NSW Department of Education—is a valid or effective tool.

Establishing localised comfort standards and benchmarks for NSW school environments could significantly improve indoor environmental quality, student wellbeing and academic performance. This would also support the design of more energy-efficient and climate-resilient school buildings that are better aligned with the needs of their users.

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References

1. Milman, O. 'Off the Charts': 2023 Was Hottest Year Ever Recorded Globally, US Scientists Confirm. *The Guardian*, 13 January 2024. Available online: <https://www.theguardian.com/environment/2024/jan/12/2023-hottest-year-record-us-scientists> (accessed on 17 May 2025).
2. Ashtiani, A.; Mirzaei, P.A.; Haghighat, F. Indoor thermal condition in urban heat island: Comparison of the artificial neural network and regression methods prediction. *Energy Build.* **2014**, *76*, 597–604. [\[CrossRef\]](#)
3. ANSI/ASHRAE Standard 55-2020; Thermal Environmental Conditions for Human Occupancy. American Society of Heating, Refrigerating and Air-Conditioning Engineers: Atlanta, GA, USA, 2020.
4. Yao, R.; Li, B.; Liu, J. A theoretical adaptive model of thermal comfort—Adaptive Predicted Mean Vote (aPMV). *Build. Environ.* **2009**, *44*, 2089–2096. [\[CrossRef\]](#)
5. Mirinejad, H.; Sadati, S.H.; Ghasemian, M.; Torab, H. Control Techniques in Heating, Ventilating and Air Conditioning (HVAC) Systems. *J. Comput. Sci.* **2008**, *4*, 777–783. [\[CrossRef\]](#)
6. Haddad, S.; Synnefa, A.; Ángel Padilla Marcos, M.; Paolini, R.; Delrue, S.; Prasad, D.; Santamouris, M. On the potential of demand-controlled ventilation system to enhance indoor air quality and thermal condition in Australian school classrooms. *Energy Build.* **2021**, *238*, 110838. [\[CrossRef\]](#)
7. Kuiri, L. Retrofitting Passive Cooling Strategies to a Brisbane School: A Case Study of the Physical and Social Aspects. Master's Thesis, School of Architecture, The University of Queensland, Brisbane, Australia, 2016. [\[CrossRef\]](#)
8. Filippin, C. Benchmarking the energy efficiency and greenhouse gases emissions of school buildings in central Argentina. *Build. Environ.* **2000**, *35*, 407–414. [\[CrossRef\]](#)
9. Singh, M.K.; Ooka, R.; Rijal, H.B.; Kumar, S.; Kumar, A.; Mahapatra, S. Progress in thermal comfort studies in classrooms over last 50 years and way forward. *Energy Build.* **2019**, *188–189*, 149–174. [\[CrossRef\]](#)
10. Stephen, J.; Bourikas, L.; Teli, D.; Bahaj, A.S.; Congreve, R. Internal thermal environment and futureproofing of a newly built, naturally ventilated UK school. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *588*, 032071. [\[CrossRef\]](#)
11. Montiel, I.; Mayoral, A.M.; Navarro Pedreño, J.; Maiques, S.; Marco Dos Santos, G. Linking Sustainable Development Goals with Thermal Comfort and Lighting Conditions in Educational Environments. *Educ. Sci.* **2020**, *10*, 65. [\[CrossRef\]](#)
12. Lamberti, G.; Fantozzi, F.; Salvadori, G. Thermal Comfort in Educational Buildings: Future Directions Regarding the Impact of Environmental Conditions on Students' Health and Performance. In Proceedings of the 2020 IEEE International Conference on Environment and Electrical Engineering and 2020 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe), Madrid, Spain, 9–12 June 2020. [\[CrossRef\]](#)
13. Sayre, R.; Karagulle, D.; Frye, C.; Boucher, T.; Wolff, N.H.; Breyer, S.; Wright, D.; Martin, M.; Butler, K.; Van Graafeiland, K.; et al. An assessment of the representation of ecosystems in global protected areas using new maps of World Climate Regions and World Ecosystems. *Glob. Ecol. Conserv.* **2020**, *21*, e00860. [\[CrossRef\]](#)
14. Shrestha, M.; Rijal, H.B.; Kayo, G.; Shukuya, M. A Field Investigation on Adaptive Thermal Comfort in School Buildings in the Temperate Climatic Region of Nepal. *Build. Environ.* **2021**, *190*, 107523. [\[CrossRef\]](#)
15. Sánchez-García, D.; Bienvenido-Huertas, D.; Martínez-Crespo, J.; de Dear, R. Using setpoint temperatures based on adaptive thermal comfort models: The case of an Australian model considering climate change. *Build. Environ.* **2024**, *258*, 111647. [\[CrossRef\]](#)
16. Ren, Z.; Chen, D. Modelling Study of the Impact of Thermal Comfort Criteria on Housing Energy Use in Australia. *Appl. Energy* **2018**, *210*, 152–166. [\[CrossRef\]](#)
17. Walsh, A.; Cóstola, D.; Labaki, L.C. Validation of the Climatic Zoning Defined by ASHRAE Standard 169-2013. *Energy Policy* **2019**, *135*, 111016. [\[CrossRef\]](#)

18. Bai, L.; Yang, L.; Song, B.; Liu, N. A New Approach to Develop a Climate Classification for Building Energy Efficiency Addressing Chinese Climate Characteristics. *Energy* **2020**, *195*, 116982. [CrossRef]
19. de Dear, R.; Kim, J.; Candido, C.; Deuble, M. Summertime thermal comfort in Australian school classrooms. In *Proceedings of the 8th Windsor Conference: Counting the Cost of Comfort in a Changing World*, Windsor, UK, 10–13 April 2014; Network for Comfort and Energy Use in Buildings: London, UK, 2014; Volume 43.
20. Shrestha, M.; Rijal, H.B. Investigation on Summer Thermal Comfort and Passive Thermal Improvements in Naturally Ventilated Nepalese School Buildings. *Energies* **2023**, *16*, 1251. [CrossRef]
21. Fabbri, K. Thermal comfort evaluation in kindergarten: PMV and PPD measurement through datalogger and questionnaire. *Build. Environ.* **2013**, *68*, 202–214. [CrossRef]
22. Yun, H.; Nam, I.; Kim, J.; Yang, J.; Lee, K.; Sohn, J. A field study of thermal comfort for kindergarten children in Korea: An assessment of existing models and preferences of children. *Build. Environ.* **2014**, *75*, 182–189. [CrossRef]
23. Singhal, P. ‘Short-Sighted’: Sydney’s New Schools to Be Built Without Air Conditioning. *The Sydney Morning Herald*, 6 February 2018. Available online: <https://www.smh.com.au/education/shortsighted-sydneys-new-schools-to-be-built-without-air-conditioning-20180205-h0tsaw.html> (accessed on 17 May 2025).
24. Díaz-López, C.; Serrano-Jiménez, A.; Lizana, J.; López-García, E.; Molina-Huelva, M.; Barrios-Padura, Á. Passive Action Strategies in Schools: A Scientific Mapping towards Eco-Efficiency in Educational Buildings. *J. Build. Eng.* **2022**, *45*, 103598. [CrossRef]
25. Kottke, M.; Grieser, J.; Beck, C.; Rudolf, B.; Rubel, F. World Map of the Köppen-Geiger Climate Classification Updated. *Meteorol. Z.* **2006**, *15*, 259–263. [CrossRef]
26. Parsons, K.C. ISO Standards and Thermal Comfort: Recent Developments. In *Standards for Thermal Comfort*; Humphreys, M., Nicol, F., Sykes, O., Roaf, S., Eds.; Routledge: London, UK, 1995; pp. 259–268.
27. de Dear, R. Thermal comfort in practice. *Indoor Air* **2004**, *14*, 32–39. [CrossRef]
28. Zomorodian, Z.S.; Tahsildoost, M.; Hafezi, M. Thermal comfort in educational buildings: A review article. *Renew. Sustain. Energy Rev.* **2016**, *59*, 895–906. [CrossRef]
29. Olesen, B.W.; Parsons, K.C. Introduction to Thermal Comfort Standards and to the Proposed New Version of EN ISO 7730. *Energy Build.* **2002**, *34*, 537–548. [CrossRef]
30. van Hoof, J.; Mazej, M.; Hensen, J.L.M. Thermal Comfort: Research and Practice. *Front. Biosci.* **2010**, *15*, 765–788. [CrossRef]
31. Fanger, P.O.; Toftum, J. Extension of the PMV model to non-air-conditioned buildings in warm climates. *Energy Build.* **2002**, *34*, 533–536. [CrossRef]
32. de Dear, R.J.; Akimoto, T.; Arens, E.A.; Brager, G.; Candido, C.; Cheong, K.W.D.; Li, B.; Nishihara, N.; Sekhar, S.C.; Tanabe, S.-I.; et al. Progress in thermal comfort research over the last twenty years. *Indoor Air* **2013**, *23*, 442–461. [CrossRef]
33. Kwok, A.; Rajkovich, N. Addressing climate change in comfort standards. *Build. Environ.* **2010**, *45*, 18–22. [CrossRef]
34. Fanger, P.O. *Thermal Comfort*; Danish Technical Press: Copenhagen, Denmark, 1970.
35. Han, H.; Lee, J.; Kim, J.; Jang, C.; Jeong, H. Thermal Comfort Control Based on a Simplified Predicted Mean Vote index. *Energy Procedia* **2014**, *61*, 970–974. [CrossRef]
36. Cheung, T.; Schiavon, S.; Parkinson, T.; Li, P.; Brager, G. Analysis of the accuracy on PMV–PPD model using the ASHRAE Global Thermal Comfort Database II. *Build. Environ.* **2019**, *153*, 205–217. [CrossRef]
37. ANSI/ASHRAE Standard 55-2023; Thermal Environmental Conditions for Human Occupancy. American Society of Heating, Refrigerating and Air-Conditioning Engineers: Atlanta, GA, USA, 2023.
38. ISO ISO/WDIS 7730:2025; Ergonomics of the Thermal Environment—Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria. International Organization for Standardization: Geneva, Switzerland, 2025.
39. International Organization for Standardization (ISO). ISO Capacity Building Portal. Available online: <https://capacity.iso.org/home.html> (accessed on 18 May 2025).
40. Pistore, L.; Varin, C.; Pasut, W. Development of Climate-Based Thermal Comfort Ranges from Existing Data: Analysis of the Smart Controls and Thermal Comfort (SCATS) Database. *Energy Build.* **2023**, *298*, 113509. [CrossRef]
41. Australian Building Codes Board (ABCB). *National Construction Code 2022*; Commonwealth of Australia: Canberra, Australia, 2025. Available online: <https://ncc.abcb.gov.au/> (accessed on 18 May 2025).
42. Green Building Council of Australia (GBCA). Green Star Rating System: Buildings. Available online: <https://new.gbca.org.au/green-star/rating-system/buildings/> (accessed on 18 May 2025).
43. Yong, T.; Djamil, H. Exploring Köppen-Geiger Climate Classification of the ASHRAE RP-884 Database. *Int. J. Recent Technol. Eng.* **2019**, *7*, 854–860.
44. Australian Building Codes Board (ABCB). *Climate Zone Map*; ABCB: Canberra, Australia, 2024. Available online: <https://www.abcb.gov.au/resources/climate-zone-map> (accessed on 18 May 2025).
45. Lam, C.K.C.; Shooshtarian, S.; Kenawy, I. Assessment of Urban Physical Features on Summer Thermal Perceptions Using the Local Climate Zone Classification. *Build. Environ.* **2023**, *236*, 110265. [CrossRef]

46. Green Building Council of Australia. *The Future of Australian Education—Sustainable Places for Learning*; Green Building Council of Australia: Sydney, Australia, 2013; Available online: https://www.gbca.org.au/uploads/167/34983/Green_Schools_report_2013_Final_for_web.pdf (accessed on 18 May 2025).
47. State of Victoria (Department of Education). *Building Quality Standards Handbook*; State of Victoria: Melbourne, Australia, 2024. Available online: <https://content.sdp.education.vic.gov.au/media/building-quality-standards-handbook-1068> (accessed on 18 May 2025).
48. NSW Government Architect. *Design Guide for Schools*; NSW Government: Sydney, Australia, 2018. Available online: <https://www.planning.nsw.gov.au/sites/default/files/2023-10/design-guide-for-schools.pdf> (accessed on 18 May 2025).
49. Office of the Government Architect. *Education Design Standard for Secondary Schools 02*; Government of Western Australia, Department of Finance: Perth, Australia, 2021. Available online: https://www.wa.gov.au/system/files/2021-05/OGA_Education_Design_Standard_02.pdf (accessed on 18 May 2025).
50. Queensland Government. *Design Standards for Department of Education Facilities Version 5.1*; Queensland Government Department of Education: Brisbane, Australia, 2025. Available online: <https://qed.qld.gov.au/our-publications/standards/Documents/design/design-standards-facilities.pdf> (accessed on 17 June 2025).
51. Tasmanian Government. *Department of Education Built Environment Guide*; Tasmanian Government Capital Works, Facility Services Department of Education: Hobart, Australia, 2020. Available online: https://www.parliament.tas.gov.au/__data/assets/pdf_file/0034/59956/department20of20education-new20legana20primary20school-submission20-20attachment20420-20doe20built20environment20guide.pdf (accessed on 17 June 2025).
52. de Dear, R.; Kim, J.; Candido, C.; Deuble, M. Adaptive thermal comfort in Australian school classrooms. *Build. Res. Inf.* **2015**, *43*, 383–398. [CrossRef]
53. Madden, A.; Arora, V.; Holmes, K.; Pfautsch, S. *Cool Schools*; Western Sydney University: Sydney, Australia, 2018. [CrossRef]
54. NESA. *Registered and Accredited Individual Non-Government Schools (NSW) Manual*; NSW Education Standards Authority: Sydney, Australia, 2020; Available online: www.educationstandards.nsw.edu.au (accessed on 10 February 2024).
55. Alghamdi, S.; Tang, W.; Kanjanabootra, S.; Alterman, D. Field Investigations on Thermal Comfort in University Classrooms in New South Wales, Australia. *Energy Rep.* **2023**, *9*, 63–71. [CrossRef]
56. New South Wales Department of Education. *Educational Facilities Standards and Guidelines (EFSG)*. Available online: <https://education.nsw.gov.au/about-us/efsg/contact-efsg> (accessed on 18 May 2025).
57. New South Wales Department of Education. *Design Framework: Sustainability v1.0*; NSW Government: Sydney, Australia, 2023. Available online: <https://education.nsw.gov.au/about-us/efsg/design-framework/sustainability> (accessed on 18 May 2025).
58. Green Building Council of Australia. *IEQ Thermal Comfort Credit—Draft D2*; GBCA: Sydney, Australia, 2013; Available online: https://www.gbca.org.au/uploads/147/35475/IEQ_Thermal%20Comfort_draft_D2_distributed.pdf (accessed on 18 May 2025).
59. Haverinen-Shaughnessy, U.; Shaughnessy, R. Effects of Classroom Ventilation Rate and Temperature on Students' Test Scores. *PLoS ONE* **2015**, *10*, e0136165. [CrossRef]
60. Goodman, J. Heat and Learning. In *NBER Working Paper No. 24639*; National Bureau of Economic Research: Cambridge, MA, USA, 2018; Available online: <https://www.nber.org/papers/w24639> (accessed on 18 May 2025).
61. Tartarini, F.; Cooper, P.; Fleming, R. Thermal Comfort for Occupants of Nursing Homes: A Field Study. University of Wollongong 2018. Conference Contribution. Available online: <https://hdl.handle.net/10779/uow.27703644.v1> (accessed on 18 May 2025).
62. Barbiero, G.; Berto, R.; Venturella, A.; Maculan, N. Bracing Biophilia: When biophilic design promotes pupil's attentional performance, perceived restorativeness and affiliation with Nature. *Environ. Dev. Sustain.* **2021**. [CrossRef]
63. Andamon, M.M.; Bellamy, L.A.; Ridley, I. Thermal environments and indoor air quality of P-12 educational facilities in Australia: A critical review of standards, regulations and policies. In *Proceedings of the Indoor Air 2014-13th International Conference on Indoor Air Quality and Climate International Society of Indoor Air Quality and Climate*, Hong Kong, China, 7–12 July 2014; pp. 964–972.
64. Andamon, M.M.; Woo, J. Indoor Environmental Quality of Preparatory to Year 12 (P-12) Educational Facilities in Australia: Challenges and Prospects. In *Energy Performance in the Australian Built Environment. Green Energy and Technology*; Rajagopalan, P., Andamon, M., Moore, T., Eds.; Springer: Singapore, 2019; Available online: https://doi-org.ezproxy.newcastle.edu.au/10.1007/978-981-10-7880-4_8 (accessed on 18 May 2025).
65. Grant, M.J.; Booth, A. A typology of reviews: An analysis of 14 review types and associated methodologies. *Health Inf. Libr. J.* **2009**, *26*, 91–108. [CrossRef]
66. Sataloff, R.T.; Bush, M.L.; Chandra, R.; Chepeha, D.; Rotenberg, B.; Fisher, E.W.; Goldenberg, D.; Hanna, E.Y.; Kerschner, J.E.; Kraus, D.H.; et al. Systematic and other reviews: Criteria and complexities. *World J. Otorhinolaryngol. Head Neck Surg.* **2021**, *7*, 236–239. [CrossRef]
67. Scholtz, S.E.; de Klerk, W.; de Beer, L.T. The Use of Research Methods in Psychological Research: A Systematised Review. *Front. Res. Metr. Anal.* **2020**, *5*, 1–17. [CrossRef]

68. Cabeza, L.F.; Chàfer, M.; Mata, É. Comparative Analysis of Web of Science and Scopus on the Energy Efficiency and Climate Impact of Buildings. *Energies* **2020**, *13*, 409. [CrossRef]
69. Martín-Martín, A.; Thelwall, M.; Orduna-Malea, E.; Delgado López-Cózar, E. Google Scholar, Microsoft Academic, Scopus, Dimensions, Web of Science, and OpenCitations' COCI: A multidisciplinary comparison of coverage via citations. *Scientometrics* **2021**, *126*, 871–906. [CrossRef]
70. Gusenbauer, M.; Haddaway, N.R. Which Academic Search Systems Are Suitable for Systematic Reviews or Meta-Analyses? Evaluating Retrieval Qualities of Google Scholar, PubMed, and 26 Other Resources. *Res. Synth. Methods* **2020**, *11*, 181–217. [CrossRef] [PubMed]
71. Elsevier. *Scopus Quick Reference Guide*; Elsevier: Amsterdam, The Netherlands, 2023; Available online: https://assets.ctfassets.net/o78em1y1w4i4/2NZ8zIh742LdKixRJpbhba/4bb0c5a017c53d79c9f5fe2999ada6a4/Scopus_Quick_Reference_Guide_WEB_2023.pdf (accessed on 18 May 2025).
72. Hulth, A. Improved Automatic Keyword Extraction Given More Linguistic Knowledge. *Sustainability* **2023**, *15*, 1234–1245.
73. Corrin, L.; Thompson, K.; Hwang, G.-J.; Lodge, J.M. The importance of choosing the right keywords for educational technology publications. *Australas. J. Educ. Technol.* **2022**, *38*, 1–8. [CrossRef]
74. Amoatey, P.; Al-Jabri, K.; Al-Saadi, S.; Al-Harthy, I.; Al-Khuzairi, M. Impact of Indoor Environmental Quality on Students' Comfort in High School Buildings during the Summer Season in an Extreme Climate. *J. Archit. Eng.* **2023**, *29*, 04023014. [CrossRef]
75. Ascanio-Villabona, J.G.; Terés-Zubiaga, J.; Muñoz-Maldonado, Y.A.; Lengerke-Pérez, O.; Del Portillo-Valdés, L.A. Assessing the Thermal Performance of a Conventional Architecture in Dry Warm Climate. *Lect. Notes Electr. Eng.* **2022**, *932*, 47–58. [CrossRef]
76. Bhatnagar, M.; Mathur, J.; Garg, V. Determining base temperature for heating cooling degree-days for India. *J. Build. Eng.* **2018**, *18*, 270–280. [CrossRef]
77. Carlucci, S.; Bai, L.; de Dear, R.; Yang, L. Review of adaptive thermal comfort models in built environmental regulatory documents. *Build. Environ.* **2018**, *137*, 73–89. [CrossRef]
78. Crosby, P.; Kochupurackal, B.T.; Rajkumar, S. Energy consumption evaluation and optimization of radiant and personalized cooling in hot-humid and dry climatic zone. *Build. Simul. Conf. Proc.* **2019**, *3*, 2011–2018.
79. Defo, M.; Sahyoun, S.; Lacasse, M.A.; Moore, T.V. Impacts of wind-driven rain calculation methods on the moisture performance of wood-frame walls. In Proceedings of the ASHRAE Topical Conference Proceedings, Atlanta, GA, USA, 12–16 January 2019; pp. 573–581.
80. Efeoma, M.; Uduku, O. Longitudinal survey of adaptive thermal comfort of office workers in the hot humid climate zone of Enugu, Nigeria. In Proceedings of the 9th International Windsor Conference 2016: Making Comfort Relevant 2016, Windsor, UK, 7–10 April 2016; pp. 478–488.
81. Eldin, M.; Badawi, M.E. HVAC System Optimization and Energy Savings at Hot Dry Climate Zones in Middle East. In Proceedings of the ASHRAE Annual Conference, Seattle, WA, USA, 28 June–2 July 2014.
82. Gallardo, A.; Macdonald, I.; Knudsen, H. Thermal Bridging Requirements in the NECB Context: Specifying Wall Clear-Field Transmittances to Compensate for Major Thermal Bridges. *Lect. Notes Civ. Eng.* **2025**, *552*, 519–526. [CrossRef]
83. Hong, S.-J.; Kim, H.-J.; Lee, J.-H.; Cho, Y.-H. Monthly high-limit setpoint of economizer system in South Korea. *Energy Rep.* **2025**, *13*, 875–884. [CrossRef]
84. Kim, H.B.; Mae, M.; Choi, Y.; Heo, J. Applicability of phase change material according to climate zones as defined in ASHRAE standard 169-2013. *Build. Environ.* **2021**, *196*, 107771. [CrossRef]
85. Kumar, S.; Singh, M.K.; Mathur, A.; Mathur, S.; Mathur, J. Thermal performance comfort potential estimation in low-rise high thermal mass naturally ventilated office buildings in India: An experimental study. *J. Build. Eng.* **2018**, *20*, 569–584. [CrossRef]
86. Parmaksiz, K.; Yesilnacar, M.I.; Karabulut, A.I. Assessing Thermal Comfort and Indoor Air Quality: In an Educational Facility of a Semi-Arid Climate Zone. *Atmosphere* **2025**, *16*, 29. [CrossRef]
87. Sánchez-García, D.; Bienvenido-Huertas, D.; Rubio-Bellido, C.; Rupp, R.F. Assessing the energy saving potential of using adaptive setpoint temperatures: The case study of a regional adaptive comfort model for Brazil in both the present and the future. *Build. Simul.* **2024**, *17*, 459–482. [CrossRef]
88. Sánchez-García, D.; Bienvenido-Huertas, D.; Pulido-Arcas, J.A.; Rubio-Bellido, C. Extending the use of adaptive thermal comfort to air-conditioning: The case study of a local Japanese comfort model in present and future scenarios. *Energy Build.* **2023**, *285*, 112901. [CrossRef]
89. Wang, S.; Yang, L.; Meng, X.; Lyu, K.; Cao, Q.; Liu, Y. Can the ASHRAE Standard 169 zoning method be applied to country-level energy-efficient building design in China? *Build. Simul.* **2023**, *16*, 1041–1058. [CrossRef]
90. Abuelnuor, A.A.A.; Mohammedali, A.A.M.; Omara, A.A.M.; Wedaa, S.A.M.; Mohammed, M.O.A.; Ahmed, A.-H.F.A.A.-H.; Mohamed, E.-M.E.E. Evaluation of Thermal Comfort in Academic Buildings at Khartoum Locality: A Case Study. In Proceedings of the 2020 International Conference on Computer, Control, Electrical, and Electronics Engineering, ICCCEEE, Khartoum, Sudan, 26–28 February 2020. [CrossRef]

91. Ali, H.H.; Al-Hashlamun, R. Assessment of indoor thermal environment in different prototypical school buildings in Jordan. *Alex. Eng. J.* **2019**, *58*, 699–711. [\[CrossRef\]](#)
92. Asif, A.; Zeeshan, M.; Jahanzaib, M. Indoor temperature, relative humidity and CO₂ levels assessment in academic buildings with different heating, ventilation and air-conditioning systems. *Build. Environ.* **2018**, *133*, 83–90. [\[CrossRef\]](#)
93. Asif, A.; Zeeshan, M. Indoor temperature, relative humidity and CO₂ monitoring and air exchange rates simulation utilizing system dynamics tools for naturally ventilated classrooms. *Build. Environ.* **2020**, *180*, 106980. [\[CrossRef\]](#)
94. Bajc, T.S.; Todorović, M.N.; Papadopoulos, A.M. Indoor environmental quality in non-residential buildings—Experimental investigation. *Therm. Sci.* **2016**, *20*, S1521–S1529. [\[CrossRef\]](#)
95. Bajc, T.; Banjac, M.; Todorović, M.; Stevanović, Z. Experimental and statistical survey on local thermal comfort impact on working productivity loss in university classrooms. *Therm. Sci.* **2019**, *23*, 379–392. [\[CrossRef\]](#)
96. Fang, Z.; Zhang, S.; Cheng, Y.; Fong, A.M.L.; Oladokun, M.O.; Lin, Z.; Wu, H. Field study on adaptive thermal comfort in typical air conditioned classrooms. *Build. Environ.* **2018**, *133*, 73–82. [\[CrossRef\]](#)
97. Hadziahmetovic, H.; Blazevic, R.; Alispahic, M.; Sunulahpasic, R. Analysis of parameters influencing the indoor air quality. In Proceedings of the 33rd DAAAM International Symposium on Intelligent Manufacturing and Automation, Vienna, Austria, 27–28 October 2022; Volume 57. [\[CrossRef\]](#)
98. Korsavi, S.S.; Montazami, A.; Zomorodian, Z.S. Evaluating thermal environment and thermal comfort in schools located in Kashan-Iran in mid-seasons. In Proceedings of the 33rd PLEA International Conference: Design to Thrive, PLEA, Edinburgh, UK, 2–5 July 2017; Volume 1, pp. 1163–1170.
99. Korsavi, S.S.; Montazami, A.; Mumovic, D. Ventilation rates in naturally ventilated primary schools in the UK; Contextual, Occupant and Building-related (COB) factors. *Build. Environ.* **2020**, *181*, 107061. [\[CrossRef\]](#)
100. Kuru, M.; Calis, G. Investigating the link between CO₂ concentration, thermal comfort and occupant perception in educational buildings. *Simul. Ser.* **2018**, *50*, 79–85.
101. Lee, M.-C.; Wong, L.-T.; Mui, K.-W.; Chang, C.-F.; Lam, W.-H. Energy conservation between natural ventilated and airconditioned classroom in Taiwan. In Proceedings of the Indoor Air 2014—13th International Conference on Indoor Air Quality and Climate, Hong Kong, China, 7–12 July 2014; pp. 247–254.
102. Li, X.; Chen, Z.; Tu, J.; Yu, H.; Tang, Y.; Qin, C. Impact of impinging jet ventilation on thermal comfort aerosol transmission: A numerical investigation in a densely-occupied classroom with solar effect. *J. Build. Eng.* **2024**, *94*, 109872. [\[CrossRef\]](#)
103. Singh, M.K.; Kumar, S.; Ooka, R.; Rijal, H.B.; Gupta, G.; Kumar, A. Status of thermal comfort in naturally ventilated classrooms during the summer season in the composite climate of India. *Build. Environ.* **2018**, *128*, 287–304. [\[CrossRef\]](#)
104. Zaki, S.A.; Damiani, S.A.; Rijal, H.B.; Hagishima, A.; Abd Razak, A. Adaptive thermal comfort in university classrooms in Malaysia and Japan. *Build. Environ.* **2017**, *122*, 294–306. [\[CrossRef\]](#)
105. Hou, X.; Tian, Z.; Niu, J.; Wu, X.; Lu, Y. Research on design day generation method for air-conditioning system design considering the coincidence of hourly variation coefficient. *Energy Build.* **2022**, *270*, 112300. [\[CrossRef\]](#)

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