BESt: Journal of Built Environment Studies
P-ISSN: 2086-2636 E-ISSN: 2356-4644
Journal Home Page: http://www.archiplan.ugm.ac.id

BETTER SPACE BETTER LIVING

ADAPTIVE THERMAL COMFORT: A LITERATURE REVIEW

Muhammad Afi Tegar Ramadhan[1*], Nedyomukti Imam Syafii[1]
[1] *Department of Architecture and Planning, Faculty of Engineering, Universitas Gadjah Mada, Yogyakarta, Indonesia*

ABSTRACT

Adaptive thermal comfort allows users to adapt themselves and their environment to achieve thermal comfort. This research is a literature review of adaptive thermal comfort, which aims to determine comparison to assess the comparison of comfort temperatures and user thermal adaptation behavior from various climatic conditions and ventilation systems. This study found that natural and mixed-mode ventilation rooms were proven to have a wider comfortable temperature range than air conditioning rooms in tropical and non-tropical non-winter climates. The findings revealed the proximity of thermal preferences in tropical and non-tropical non-winter climates in terms of comfort temperature and clothing insulation in natural and mixed-mode ventilation rooms (26.0 °C and 25.6 °C, and 0.60 clo and 0.62 clo, respectively). The toughest adaptation is found in winter climates, with high clothing insulation, even when the heater is turned on. Clothing insulation is negatively correlated to operative and comfort temperatures. Through the discovery of wide comfortable temperature ranges in naturally ventilated rooms and the increasing interest in adaptation to windows and fans, air velocity has the potential to be an energy-saving strategy to achieve thermal comfort.

[*]Corresponding Author

Muhammad Afi Tegar Ramadhan
Universitas Gadjah Mada
Email :
muhammadafitegarramadhan@mail.ugm.ac.id

Keywords:
Adaptive, thermal comfort, behavior, ventilation, literature review

1. Introduction

Thermal comfort is one of the main concerns in responding to environmental issues. One of the causes of this environmental problem is the large amount of energy used for artificial ventilation in buildings. Strategies to achieve user thermal comfort are solutions to minimize artificial ventilation while creating a comfortable environment for building users (de Dear et al., 2020). Based on the American National Standards Institute (ANSI) and American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 55, thermal comfort is a state of mind that indicates satisfaction with the thermal environment (de Dear et al., 2020).

After going through various research developments, conventional thermal comfort has developed into another alternative: adaptive thermal comfort. Adaptive thermal comfort is based on the failure of the conventional thermal comfort principle, namely "one size fits all". This principle cannot meet users' thermal comfort requirements in different conditions and backgrounds. Adaptive thermal comfort is claimed to provide users with thermal comfort with higher temperatures and a wider range (de Dear et al., 2020). Research on adaptive comfort continues to develop, especially in the Asian region, since the first publication by Nicol and Humphreys in 1973 (Parkinson et al., 2020).

The principle of adaptive thermal comfort is based on human behavior. An adaptive approach can adjust needs according to the user's background, behavioral preferences, metabolism, gender, age, and physical abilities. Adaptive thermal comfort has the principle that users who have the opportunity to adapt to their thermal environment will be further away from feeling uncomfortable (Nicol & Humphreys, 2002).

Adaptive thermal comfort research development is interesting to study in order to provide building design solutions amidst current environmental issues. This research will conduct a literature review of 40 adaptive thermal comfort studies in various countries. This literature review is expected to help researchers, architects, and other building experts understand the development of adaptive thermal comfort and its benefits to users. The study aims to unlock knowledge of adaptive thermal comfort in different climates and ventilation systems to provide an initial idea for building designers to achieve thermal comfort efficiently. This research is also expected to provide insight into users' thermal adaptation behavior as a consideration in designing the proper ventilation system.

The objectives of this literature review are as follows:

1. Comparing user comfort temperatures from various adaptive thermal comfort studies based on climate and type of ventilation.
2. Comparing the insulation value of clothing from various studies based on climate and type of ventilation.

Identify thermal adaptation behaviors that are often researched and carried out by users in various climatic conditions

2. Literature Review

Adaptive thermal comfort has been widely studied in naturally ventilated buildings and a combination of natural and artificial ventilation (mixed mode). This ventilation system can provide flexibility to users to adjust thermal comfort according to their preferences. This strategy allows the user to control thermal comfort by minimizing artificial ventilation. Using natural ventilation is a strategy to maintain room conditions in a broader range of temperature points (Parkinson, 2020). Nicol and Humphreys (2002) added that the adaptive approach includes changing clothing, activities, posture, and air movement according to the user's comfort. This form of adaptation does not always have immediate effects, but this strategy allows users to change environmental conditions according to their desires.

Adaptive thermal comfort also takes the user's body heat balance into account. This concept developed by Macpherson explains that the heat balance felt by the user is influenced by personal and environmental parameters (Karyono et al., 2020). Environmental parameters include air temperature, radiant temperature, wind speed, and humidity (Karyono, 2020). Personal parameters represent user characteristics, which include clothing insulation, average metabolic heat, and activity level (Enescu, 2017). Personal parameters are often measured by ASHRAE standards, namely thermal sensation, thermal acceptability, thermal comfort, thermal preference, and clothing insulation value (clo) (KC et al., 2018). The 7-point scale thermal sensation parameters, often used to survey users' thermal comfort according to ASHRAE guidelines, can be seen in Table 1.

Another calculation to measure a user's thermal comfort is through PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied), which Fanger put forward in the book "Thermal Comfort" in 1970. PMV and PPD are currently used by ISO Standard 7730 as thermal comfort parameters. Thus, through PMV and PDD calculations, researchers can predict the user's general thermal sensation and the user's level of discomfort when exposed to moderate thermal environments (Alfano et al., 2017). These standards are often used as measuring tools by researchers to identify users' thermal comfort in various studies, and these standards have increased over the last decade. The topic of thermal comfort continues to develop, and adaptive models are emerging based on the user's and his environment's adaptation. So, the calculation results for the comfort temperature range presented differ from conventional thermal comfort and tend to be wider (de Dear et al., 2020).

Table 1. Thermal Comfort Scales

Thermal sensation	
-3	Cold
-2	Cool
-1	Slightly cool
0	Neutral
1	Slightly warm
2	Warm
3	Hot
Thermal preference	
-2	Much warmer
-1	Slightly warmer
0	No change
1	Slightly cooler
2	Much cooler
Thermal acceptability	
1	Acceptable
2	Not acceptable
Overall comfort	
1	Very cool
2	Comfortable
3	Slightly comfortable
4	Slightly uncomfortable
5	Uncomfortable
6	Very uncomfortable
Thermal sensation 7-point scale of ASHRAE	

Source: Zaki et al., 2017

3. Research Method

This research is a literature review. It reviews 40 studies of adaptive thermal comfort, as shown in Table 2. Research sources include journals and symposiums that have been published internationally. The search for research was carried out through e-surveys and literature studies. This research was filtered based on publication years 2013-2024 and the keywords "adaptive" and "thermal comfort" in various countries, building typologies, and climates.

This literature review will discuss the analysis of thermal comfort results, the analysis of clothing insulation values, and the adaptation of user behavior to achieve thermal comfort. From each study, we compared the average findings of thermal comfort, clothing insulation, and adaptive behavior to be compared and analyzed statistically. Statistical analysis is necessary to compare each aspect's averages and standard deviations.

We also conduct statistical analysis based on ventilation and climate groups to examine the aspects we want to discuss specifically on climate and specific ventilation. Discussions based on ventilation systems and climate are also grouped to facilitate comparison. Our statistical data presents graphs to facilitate the comparison process, find a diversity of acceptable comfort from various studies, and discuss its findings. Other findings from each study relevant to the selected aspects of the discussion (thermal comfort, clothing insulation, and adaptive behavior) are also discussed to support a more holistic discussion of the findings. The results of the statistical analysis of each aspect and findings from previous research are discussed with each other to draw conclusions and recommend future research and design opportunities.

4. Results and Discussions

4.1 Analysis Based on Comfortable Temperature

Adaptive thermal comfort research results discussed in this sub-chapter are the user's comfortable temperature in each study. The research results were grouped based on climate conditions when the research was conducted. The first group is research in tropical climate conditions, while the second is in non-tropical climate conditions with more varied seasons. We also divide the non-tropical climate group into two, namely the non-tropical non-winter climate group and the non-tropical winter climate group. The categorization is because winter temperatures are very low, so we want more details. It was found that the average comfortable temperature in research in tropical climates tended to be higher than in non-tropical climates (Table 3). The results of these studies show that the average comfortable temperature is greatly influenced by the environmental (outdoor) temperature conditions experienced by the user.

Table 2. List of thermal comfort and insulation values of clothing from reviewed research

No	Reference	Typology	Location	Climate	Mode	Average Comfortable Temperature (°C)	Average Clothing Insulation (clo)
1	Barbadilla-Martín et al. (2017)	office	Spain	Mediterranean	MM	23.6	0.86
2	Damiati et al. (2016)	office	Malaysia	tropical - summer	CL	24.3	0.62
			Indonesia		FR	26.7	0.58
					MM	27.2	0.59
					CL	25.9	0.52
			Singapore		CL	23.3	0.57
			Japan		FR	26.5	0.51
					CL	25.9	0.53
3	de Dear et al. (2015)	school	Australia	temperate, subtropical, and semi-arid	NV and AC	22.5	0.45
4	Faheem et al. (2023)	hostel	India	warm humid	NV	29.5	0.4
5	Guo Y. et al. (2023)	office	China	summer	ECA	28.7	0.32
					NV	29.2	0.28
6	Mohammadpourkarbasi et al. (2022)	school library	Ghana	tropical	NV	30.3	0.55
					AC	27.4	0.57
7	Haddad et al. (2016)	Primary school	Shiraz, Iran	cool	NV	23.4	0.7
				warm	NV	25.3	0.7
8	Indraganti et al. (2014)	office	India	warm, humid, and composite	NV	28	0.7
					AC	26.4	
9	Jiang (2020)	primary and secondary school	China	winter	HT - controlled (lowest)	14.8	1.6
					HT - controlled (highest)	17.7	1.6
					HT - uncontrolled (lowest)	12.6	1.4
					HT - uncontrolled (highest)	16.9	1.4
10	Jiao et al. (2020)	residential building (elderly)	Shanghai, China	hot summer - cold winter	NV winter	19.4	
					NV summer	27	
					NV mid season	31.7	
11	KC et al. (2018)	multi-story condominium	Japan	summer, winter, autumn, and spring	Overall	22.8	
					FR - summer	26.2	0.4
					FR - winter	19.3	0.84
					FR - autumn	23.6	
					FR - spring	22.9	
					CL	27.2	
					HT	19.9	
12	Khalid et al. (2019)	hospital	Malaysia	tropical	CL (patient)	23.5	1.84
					CL (visitor)	23.2	0.43
13	Liu et al. (2020)	coastal residential building	Hainan, China	tropical moist	NV winter	25.44	0.77
14	López-Pérez et al. (2019)	Educational Buildings	Tuxtla Gutierrez Mexico	tropical aw	AC	25.9	0,.62
					NV	26.1	0.61

No	Reference	Typology	Location	Climate	Mode	Average Comfortable Temperature (°C)	Average Clothing Insulation (clo)
15	Mishra & Ramgopal (2015)	residences, office buildings, classrooms, and a railway waiting Lounge.	India	tropic	AC	27	
					NV	27.6	
					AC	26.4	
					NV	28	
					AC	26.1	
					NV	28.1	
					AC	26.4	
					NV	28	
16	Forcada et al. (2021)	nursing house	Spain	winter and hot	NV winter (lowest)	22.5	
					NV winter (highest)	24.5	
					NV summer (lowest)	25.5	
					NV summer (highest)	26.0	
					AC Heating	23.1	
					AC Cooling	24.6	
17	Aparicio-Ruiz et al. (2021)	school	Spain	Summer	NV	24.5	0.3
					AC	27.4	0.3
18	Zheng et al. (2022)	office	China	hot summer - warm winter	AC Cooling	25.5	
					AC Heating	28.4	
19	Rawal et al. (2022)	residential	India	hot, dry, warm, humid, composite, Temperate, and cold	NV and MM (lowest)	18.2	0.1
					NV and MM (highest)	38.3	1
20	Rijal et al. (2019)	residential	Japan	winter, spring, summer, and autumn	FR	23.6	0.2
					CL	27	0.8
					HT	19.9	
					FR - winter	17.6	
					FR - spring	21.6	
					FR - summer	27	
					FR - autumn	23.9	
21	Rijal et al. (2015)	office	Japan	warm & humid, hot & dry, composite, Moderate and cold.	FR	26.8	
					CL	27.2	
22	Rijal et al. (2017)	Office	Japan	summer, winter, autumn, and spring	FR	25	
					CL	25.4	
					HT	24.3	
23	Rupp et al. (2018)	Office	Florianopolis, Brazil	temperate humid climate (summer and winter)	NV Building H1	22.6	0.8
					AC Building H1	24.6	0.57
					NV Building H2	23.6	0.7
					AC Building H2	24	0.65
					NV Building H3	23.9	074
					AC Building H3	24.2	0.61
24	Singh et al. (2023)	office	India	warm humid, cold humid, and cold cloudy	NV all seasons	25.6	0.9
					NV - warm, humid	26.4	0.75
					NV - cold, humid	24.7	0.88
					NV - cold, cloudy	23.4	1.15
25	Singh et al. (2017)	Office	North-East India	autumn	NV	27.3	0.8

No	Reference	Typology	Location	Climate	Mode	Average Comfortable Temperature (°C)	Average Clothing Insulation (clo)
26	Song et al. (2017)	Residential	China	Cold	MM (lowest)	21	
					MM (highest)	27.3	
27	Takasu et al. (2017)	office	Tokyo and Kanagawa, Japan	summer, winter, autumn, and spring	FR lower	20	
					FR upper	28	
					MM lower	23.5	
					MM upper	26.6	
28	Thapa et al. (2017)	residential buildings	north-east India	temperate climates (subtropical, cool, and warm seasons)	NV 1st location	21.2	0.7
					NV 2nd location	17.51	0.9
29	Trebilcock et al. (2017)	Primary School	Chile	winter and spring	NV winter lower	14.7	
					NV winter upper	15.6	
					NV spring lower	22.5	
					NV spring upper	23.1	
30	Vergés et al. (2023)	nursing home	Spain	Mediterranean and continental Mediterranean	direct expansion system and variable refrigerant volume	26.0	
31	Williamson & Daniel (2020)	Residential	Australia	temperate climates	MM	20.5	
32	Wu et al. (2019)	dormitory	China	winter and summer	NV	26.2	0.39
33	Xu et al. (2018)	Traditional Dwellings	China	hot summer and cold winter	AC winter lower	10.6	2.07
					AC winter upper	28.5	
					AC summer lower	22.0	0.46
					AC summer supper	30.1	
34	Yau et al. (2013)	hospital	Malaysia	tropical	CL	26.4	0.052
35	Yadeta et al. (2023)	residential	Ethiopia	cold, dry, hot, and fall	NV (lowest)	23.3	0.64
					NV (highest)	23.3	0.78
36	Yue & Zhongqing (2023)	residential building	Shaoxing, China	spring, summer, autumn, and winter	mixed-mode spring	25.2	0.8
		residential			mixed-mode summer	26.1	0.38
		residential			mixed-mode autumn	21.3	0.9
		residential			mixed-mode winter	19.6	1.1
37	Zaki et al. (2017)	university classroom	Malaysia	tropical - summer	FR (lowest)	26.8	0.59
					FR (highest)	26.8	0.62
					CL	25.6	0.51
			Japan	summer	FR	25.1	0.45
					CL	26.2	0.45
38	Allah et al. (2023)	office	Malaysia	tropical	Overall	26.7	
					Semi-outdoor (lowest)	22.1	0.59
					Semi-outdoor (highest)	29.2	0.74

No	Reference	Typology	Location	Climate	Mode	Average Comfortable Temperature (°C)	Average Clothing Insulation (clo)
					Indoor (lowest)	22.2	0.75
					Indoor (highest)	23.8	1.45
					Indoor open (lowest)	22.6	
					9Indoor open (highest)	25.9	
39	Zheng et al. (2022)	nursing home	China	winter, transition, and summer	MM - winter	19.4	1.51
					MM - transition	22.6	1.01
					MM – summer	24.1	0.4
40	Zhou et al. (2024)	residential (elderly)	China	summer	NV and AC	31.0	0.31

Table 3. Average Comfortable Temperature in All Climates and Overall Ventilation System

Climate	Average Comfortable Temperature (°C)	Standard Deviation
Tropical	26.0	1.98
Non-tropical (overall)	23.8	4.25
Non-tropical (non-winter)	25.6	2.95
Non-Tropical (winter)	20.3	4.32

Table 4. Average Comfortable Temperature based on Ventilation System

Climate	Mode	Average Comfortable Temperature (°C)	Standard Deviation
Tropical	NV and MM	26.8	2.15
	AC	25.2	1.57
Non-Tropical - Non-Winter	NV and MM	25.5	3.25
	AC	26.0	1.96
Non-Tropical - Winter	NV and MM	20.7	3.17
	HT	19.7	5.96

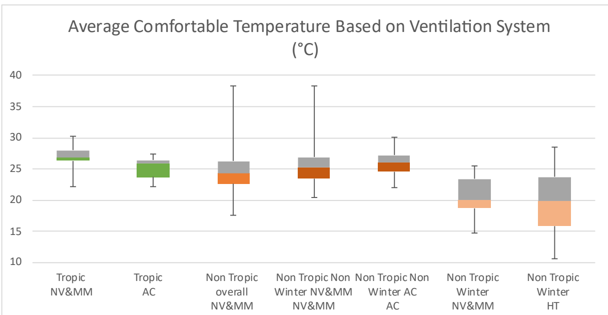

Figure 1. Average Comfortable Temperature Comparison in All Climates and Overall Ventilation System

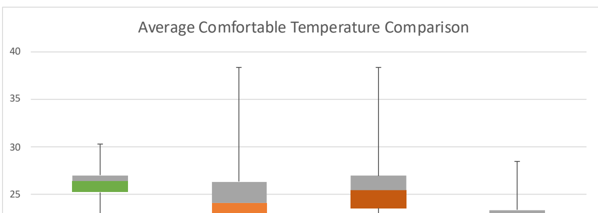

Figure 2. Average Comfortable Temperature Comparison in All Climates based on Ventilation System

4.1.1 Thermal Comfort in Tropical Climate

As mentioned, the average comfortable temperature for users in tropical climates is 26.0 ºC, almost close to the comfortable temperature in non-tropical areas in non-winter conditions. Figure 1 also shows that the comfortable temperature range for tropical climate users is the narrowest among all other comfortable temperature conditions. In Table 3, it is also demonstrated that the standard deviation of thermal comfort in tropical areas is the smallest compared to non-tropical areas. Therefore, the number of seasons in tropical regions is fewer and tends to be the same throughout the year, making the user's thermal preference range narrower and variations in comfort temperature between users are insignificant. The form of adaptation that involves air circulation often used is windows and fans.

There are three types of ventilation found in tropical climates, namely naturally ventilated (NV), mixed-mode (MM), and air-conditioner (AC). The average comfortable temperature in tropical areas with NV and MM types of ventilation tends to be higher than the comfortable temperature in rooms that use AC. The average comfortable temperature in NV and MM modes is 26.8ºC, while AC mode is 25.2ºC. These findings can support the argument of de Dear et al. (2020) that users can adapt to higher temperatures through the involvement of air circulation that can be accommodated by natural ventilation. The effect of air velocity on thermal comfort still needs to be studied further.

The high temperatures are comfortable in NV and MM modes, even exceeding 29 ºC, as found in the research of Allah et al. (2023) and Mohammadpourkarbasi et al. (2022). From Table 2, the comfort temperature in the semi-outdoor room and NV mode in the research of Allah et al. (2023) and Mohammadpourkarbasi et al. (2022) was 29.2 ºC and 30.3 ºC, respectively, which is higher than in AC mode.

The comfortable temperature difference between NV and mechanical modes in tropical, non-tropical, non-winter, and non-tropical winter climates is 1.6 ºC, 0.5 ºC, and 1.0 ºC, respectively. These findings indicate that mechanical ventilation systems in tropical climates significantly affect users' thermal comfort more than in non-tropical climates. This is proven at comfortable temperatures in tropical climates with very low AC modes (far below the average tropical comfortable temperature of 26 ºC) found in research by Allah et al. (2023), Khalid et al. (2019), and Damiati et al. (2016). It is essential to pay attention to the use of AC to avoid overcooling and wasting energy.

Based on the standard deviation (Table 4) and comfortable temperature range (Figure 2) in tropical climates, the user's thermal comfort tends to be more variable in NV mode than in AC mode. The presence of AC narrows the user's comfortable temperature range. More attention is needed to understand users' culture, character, psychology, and physical condition in NV and MM rooms. Because of this broad, comfortable temperature range, user flexibility in adapting to room thermals must be considered.

4.1.2 Thermal Comfort in Non-Tropical Climate

The second climate group is non-tropical, with comfort temperature findings that tend to be lower than tropical climates. As mentioned, the average comfortable temperature in non-tropical climates (23.8 ºC) was lower than in tropical climates (26.0 ºC). The influence of the winter season causes the average comfortable temperature in non-tropical climates to be lower than in tropical climates (table 3). This again shows that climate and outdoor temperature greatly influence the user's thermal comfort level. The colder the climate conditions, the lower the comfortable temperature the user receives, and vice versa. The outdoor temperature range in non-tropical climates is broader, and the number of seasons is more diverse, causing the range of comfortable temperatures in non-tropical climates to be wider than in tropical climates (Figure 1). However, suppose we separate the non-tropical climate into non-tropical non-winter and non-tropical winter. In that case, we get a similarity in thermal comfort between the non-tropical, non-winter, and tropical climates (Table 3). This similarity shows the closeness of preferences between users in tropical and non-tropical areas for temperatures that tend to be hot. Users in non-tropical areas can survive at tropical environmental temperatures because they have close thermal comfort preferences. Significant differences were seen in winter conditions. When the outdoor temperature drops, the user's comfort temperature also lowers. This indicates that users make several adaptation efforts to feel comfortable at lower temperatures.

Uniquely, the highest and lowest comfortable temperatures were found in research in non-tropical areas. Comfortable temperatures exceeding 30 ºC are found in India and China in NV and MM modes (Rawal R. et al., 2022; Zhou et al., 2024; Jiao et al., 2020). The lowest comfortable temperatures (below 19 ºC and even reaching 12.6 ºC) are found in research in cold climate conditions (Jiang, 2020; Rawal et al., 2022; and Rijal et al., 2019). It is challenging for architects in non-tropical climates to understand a broader range of user thermal preferences.

Ventilation systems in non-tropical climates are more diverse, namely NV, MM, AC, and HT (heating) modes. HT mode is found in winter, where users use the heater as a thermal adaptation, and AC mode is found in summer. The average comfortable temperature can be found in Table 4 and Figure 2. The comfortable temperature difference between NV and mechanical modes in tropical, non-tropical, non-winter, and non-tropical winter climates is 1.6 ºC, 0.5 ºC, and 1.0 ºC, respectively. The finding shows that thermal comfort in NV and AC rooms in non-tropical, non-winter climates is not much different. Users in non-tropical climates do not use AC and HT to regulate room temperature significantly and avoid overcooling. This behavior is related to the user's awareness of the environment.

Similar to the findings in tropical climates, the standard deviation in the AC mode is lower than that in the NV and MM modes in non-tropical climates. (Table 4). It is similar to the temperature range in the NV and MM modes, which is also more expansive than the AC (Figure 2) mode. AC makes the user's comfortable temperature more uniform than NV mode. This further strengthens the fact that AC can instantly regulate the temperature and make the user's thermal comfort at a close temperature point. The findings were also found in tropical climates, corroborating the comfort range in NV and MM rooms. This will relate to air conditioning, which will be explained in the next sub-chapter. Something that also needs to be considered is that the comfortable temperature range in non-tropical, non-winter areas is more expansive than in tropical climates. This is influenced by the seasons in non-tropical regions, which are more numerous, and not only summer but also transition seasons, autumn, spring, and so on.

From Table 4, the comfortable temperature difference between NV and heating (HT) modes in non-tropical climates in the winter season is more significant than the difference between NV and AC modes, namely 1.0ºC. However, the standard deviation of comfortable temperatures in HT mode is higher than NV and MM modes in non-tropical winter climates (even higher than other climates and modes). This case is interesting; while NV mode in other climates shows a wider comfortable temperature range, NV mode in winter climates is narrower than HT mode. This indicates that users are more flexible in setting the desired temperature via the heater. In NV mode, the user's features for adapting to extreme cold conditions are more limited, so the comfortable temperature range is also narrower. The use of a heater is still essential in winter climate conditions. Icy temperature conditions cause users' thermal comfort to be more complex with diverse heater usage preferences.

Adaptation to cold outdoor temperatures is more complex than to hot outdoor temperatures. This condition is further strengthened if the user is sick or clothing regulations bind but do not comply with the standard clothing insulation value in winter situations. Researchers and architects must consider thermal comfort in non-tropical areas during winter conditions. This is proven by the high clothing insulation (1.61 clo) even when the heater is turned on. Extreme cold temperatures make user adaptation increasingly complex and challenge researchers and architects to identify comfortable temperatures that suit user adaptation behavior.

4.1.3 Compliance with Comfort Temperature and Thermal Comfort Standards

Based on the results of each journal, the comfortable temperature received by users is not entirely by thermal standards. 13 of the 40 studies we reviewed revealed discrepancies in thermal comfort results and standards. Most of the 13 studies have different temperature ranges recommended by the ASHRAE standard. Several other studies also do not comply with the standards of their respective countries. This strengthens the criticism of the adaptive approach to the “one size fits all” principle used in conventional thermal comfort theory. A standard cannot meet all the conditions of different users, locations, and climates. An adaptive approach must consider climate factors, building systems, and the user's characteristics to determine accurate thermal comfort.

Table 5. User-comfortable temperature findings do not conform to thermal comfort standards

Reference	Disconformity with standards
Wu Z. et al. (2019), Jiang (2020), Zaki et al. (2017), Aparicio-Ruiz et al. (2021), Faheem et al. (2023), Rawal et al. (2022), Indraganti et al. (2014), Jiang et al. (2020), and Singh et al. (2023)	ASHRAE Standard
Khalid et al. (2019)	DOSH 2010 23-26
Khalid et al. (2019)	MS 1525-2014 24-40
Mohammadpourkarbasi et al. (2022), Indraganti et al. (20214)	CIBSE’s guide comfort zone
Indraganti et al. (2014)	NBC Standard
Rijal et al. (2019)	CEN Standard
Indraganti et al. (2014)	NBC (the National Building Code of India) standard

These studies went through various stages to find adaptive thermal comfort models and temperatures for each place and condition. Several measurement stages in these studies are thermal measurements through PMV (Predicted Mean Vote) and TSV (Thermal Sensation Vote) measurements. PMV and TSV measurements are carried out to determine the user's thermal comfort relative to room temperature conditions. Eight studies revealed that the PMV value was different from the TSV results, namely in the research of Barbadilla-Martín et al. (2017), Damiati et al. (2016), Jiang (2020), Muhammadpourkarbasi et al. (2022), Faheem et al. (2023), Guo et al. (2023), Takasu et al. (2017) and Allah et al. (2023). The slope regression value of PMV tends to be higher than TSV. This shows room operating temperature changes significantly impact the user's thermal comfort when calculated via PMV. However, the thermal comfort value through TSV measurements is lower than PMV, indicating that users can adapt to their environment. Thus, an increase in operative temperature does not significantly impact the demand for comfortable temperature as described by PMV. TSV also shows that adaptations have been made to reduce the user's sensitivity to changes in temperature. These differences demonstrate the importance of various calculations and user adaptation analyses in thermal comfort research.

4.2 Analysis Based on Clothing Insulation

Table 6 shows variations in clothing insulation for each user in various countries, climates, and ventilation systems. All studies revealed a negative relationship between the insulation value of clothing and the operating room temperature value. The lower the operating room temperature, the higher the clothing insulation (clo) value. Users have an adaptation to wear thicker clothing in colder environments and thin clothing in warmer environments. This finding is demonstrated by the winter clothing insulation, which is more significant than in non-cold seasons or tropical climates.

Table 6. Average Clothing Insulation

Climate	Clothing Insulation (clo)	Standard Deviation
Tropical	0.66	0.36
Non-Tropical (overall)	0.75	0.41
Non-Tropical (non-winter)	0.60	0.23
Non-Tropical (winter)	1.14	0.50

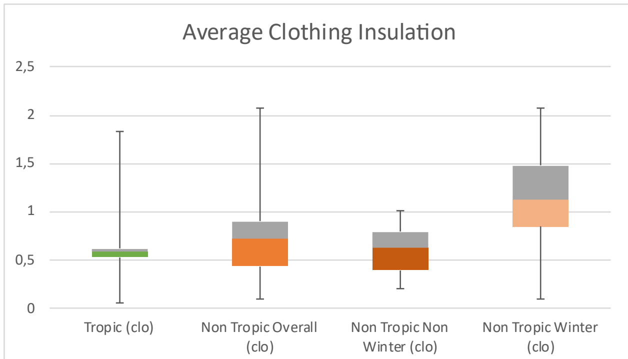

Figure 3. Average Clothing Insulation Comparison in All Climates

There is a correlation between comfortable temperature and clothing insulation. The correlation was calculated using Spearman's correlation. From Table 2, 29 out of 40 articles mention the results of comfortable temperature and clothing insulation value. Each study's comfort temperature and clothing insulation data were sorted into ordinal variables. After becoming an ordinal variable, the data was calculated using Spearman's correlation, and a Rho correlation of 0.47 was obtained. According to Spearman's rank order, this correlation is included in the strong correlation (Table 7). These findings show a reasonably strong correlation between the type of clothing used and the user's comfortable temperature. If the user's desired comfortable temperature is low, the user will wear thicker clothing with higher insulation. And if the user feels comfortable at high temperatures, the user will wear thin clothing with lower insulation. This correlation is not in a robust category because adaptation through clothing selection is not the only thermal adaptation carried out by users. There are still many other adaptations, which will be explained in the next chapter.

Table 7. Spearman Rank-Order Correlation Coefficient

Spearman	Correlation
0.70	Powerful relationship
0.40 - 0.69	Strong relationship
0.30 - 0.39	Moderate relationship
0.20 - 0.29	Weak relationship
0.01 - 0.19	No or negligible relationship
This correlation applies to positive or negative relationships.	

Table 2 shows two studies in tropical climates with findings of clo values that far exceed the average, namely in the study of Khalid et al. (2019) and Allah et al. (2023). In Khalid et al. (2019) research with a hospital research object, the clothing insulation value reached 1.84 clo because the user was a sick patient. Meanwhile, the insulation value of visitors' clothing only reached 0.43 clo. Therefore, Khalid et al. (2019) emphasized that the user's health condition can significantly influence the user's thermal preferences. Meanwhile, in the research of Allah et al. (2023), the high insulation value of clothing is influenced by applicable clothing and uniform regulations.

Research conducted by Allah et al. (2023) revealed that tight uniforms resulted in clothing insulation not complying with ASHRAE standards and user comfort with an acceptance rate of only 55%. However, clothing regulations are not strictly regulated, allowing users to customize clothing. In that case, the insulation value of clothing can comply with ASHRAE 55-2020 standards with a higher acceptance rate of 85%. These findings strengthen the flexibility aspect promoted by the adaptive thermal comfort concept. Flexibility is essential so that users can independently adjust the thermal comfort they want according to each person's background, thermal preferences, and behavior. Office and school management must consider the suitability of clothing insulation and room temperature. This is intended so that users can make clothing thermal adaptation and not rely on air conditioning.

Uniquely, the standard deviation and the insulation range of clothing for users in tropical climates are higher than in non-tropical, non-winter climates (Table 6 and Figure 3). Even though users in tropical climates only have two seasons, less than the number of seasons in non-tropical areas, the clothes used are more varied, thin, and thick. The causes of this condition have been previously explained in the research of Khalid et al. (2019) and Allah et al. (2023). Health, clothing culture, and clothing regulations significantly impact the user's thermal comfort.

There are several interesting things about clothing adaptations from the studies reviewed. Among them is that women's clothes are thicker than men's. Guo Y. et al., 2023; Yadeta et al., 2023 and Rijal et al. (2019). Likewise, the cultural influence of clothing that women often wear, such as hijab, sari, and turban, makes the insulation of women's clothing higher than men's, although this requires further study (Yau et al., 2013; Rawal et al., 2022, and Singh et al., 2023). These findings suggest that gender also has an essential impact on users' thermal comfort.

Table 8. Average Clothing Insulation based on Ventilation Systems

Climate	Average Clothing Insulation (clo)	Standard Deviation
Tropical (NV)	0.60	0.06
Tropical (AC)	0.71	0.48
Non-Tropical, Non-winter (NV and MM)	0.62	0.24
Non-Tropical Non-Winter (AC)	0.49	0.15
Non-Tropical Winter (NV and MM)	0.86	0.37
Non-Tropical Winter (HT)	1.61	0.27

Table 8 compares clothing insulation based on the ventilation system used. Clothing insulation in tropical climates in AC mode is higher than in NV mode. This aligns with comfortable temperatures in tropical climates in AC mode, lower than NV mode. The results strengthen the negative relationship between comfortable temperature and clothing insulation. Users in tropical climates can feel comfortable at higher temperatures in NV mode by wearing thinner clothing. Light clothing also increases the user's opportunity to experience air circulation to maximize adaptation in a naturally ventilated room. On the other hand, users feel comfortable at lower temperatures when using air conditioning and adapt by wearing thicker clothing.

As for non-tropical climates, clothing insulation in NV mode is higher than in AC mode. This is also in line with the acceptable temperature in non-tropical climates in NV mode, which is lower than in AC mode. Users in non-tropical climates can feel comfortable at lower temperatures in NV mode by wearing thicker clothing. The difference in clothing insulation in NV mode in tropical (0.60 clo) and non-tropical climates (0.62 clo) is very close, indicating that the clothing preferences of users in tropical and non-tropical in hot conditions are also almost the same.

Based on standard deviation, users in tropical climates NV and MM have the least variation in clothing insulation (standard deviation 0.06). This is unique because, on the other hand, the temperature is comfortable in the tropical climate of NV, and MM modes have a wide range. This suggests that users in tropical climates are comfortable at different temperatures, although the clothes used are identical between users. The difference in comfortable temperatures in tropical climates is influenced by aspects other than clothing, such as behavior, psychology, and metabolism. However, in air conditioning rooms, variations in the type of clothing used by users in tropical climates are increasingly visible (standard deviation 0.48). Even the standard deviation in tropical climates of air conditioning mode is the highest of the others. Air conditioning can significantly influence the selection of clothing for use in tropical climates.

The difference in clothing insulation in NV mode and mechanical ventilation mode in tropical, non-tropical (non-winter), and non-tropical (winter) climates is 0.11, 0.13, and 0.75, respectively. The most significant difference is found in non-tropical climates during winter conditions. According to the previous sub-chapter explanation, the difference between comfortable temperatures in NV and mechanical mode in winter is also the largest compared to warm seasons. The average clothing insulation in the cold climate of NV is 0.86 clo, which is quite far below the HT mode, namely 1.61 clo. Clothing insulation in HT mode is far above the average overall clo in winter climates (1.14 clo). This shows how cold the outdoor temperature conditions are in HT mode, so users must wear very thick clothes even when the heater is turned on. Users can only switch to NV mode with lighter clothing when the temperature is no longer freezing.

4.3 Analysis Based on Adaptive Thermal Behavior

User adaptation behavior to temperature can manifest in various forms. The 40 papers discuss adaptation through window use, fan use, AC use, and metabolism. The most frequently found forms of adaptation are through windows, fans, and air conditioning.

Table 9. Average Adaptive Behavior in All Climates

Adaptive Behavior	Average Usage (%)	Standard Deviation
Window	46.8	31.3
Fan	32.5	27.4
AC	18.6	14.5

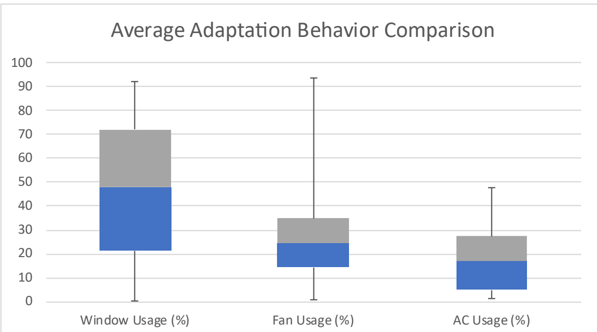

Figure 4. Comparison Of Adaptation Behavior

4.3.1 Adaptation through the use of windows

The adaptation with the most significant average usage percentage is the window usage adaptation, with a usage percentage of 46.8%. Table 10 shows the rate of window use in each study. Window usage percentages exceeding 80% were found in studies in China and India (Jiao, 2020; Yue & Zhongqing, 2023; Guo et al., 2023; and Indraganti et al., 2014). A total of 13 studies discussing windows prove that adaptation through openings is still the main topic of discussion in adaptive thermal comfort research.

Table 10. The list of studies that discuss windows and their usage percentages

Reference	Location	Mode	Window Usage (%)
Damiati et al. (2016)	Malaysia	CL	8
		FR	22.6
		FR	3
Faheem et al. (2023)	India	NV	74
Guo et al. (2023)	China	ECA	59
		NV	82.4
Indraganti et al. (2014)	India	NV	87
		AC	50
Jiao et al. (2020)	Shanghai, China	NV winter	31.9
		NV summer	92.1
		NV mid season	67.6
KC et al. (2018)	Japan	FR - summer	21
Aparicio-Ruiz et al. (2021)	Spain	NV	0.27
Rijal et al. (2019)	Japan	FR	24.1
Singh et al. (2017)	North-East India	NV	70
Song et al. (2017)	China	MM (lowest)	46.3
		MM (highest)	46.3
Yadeta et al. (2023)	Ethiopia	NV (lowest)	72
		NV (highest)	72
Yue & Zhongqing (2023)	Shaoxing, China	mixed-mode spring	86.1
		mixed-mode summer	88.7
		mixed-mode autumn	61.2
		mixed-mode winter	35
Zaki et al. (2017)	Malaysia	FR (lowest)	5
		FR (highest)	5
		FR	5

The study also shows that thermal comfort can be achieved through natural ventilation. So, in modern times, there is still potential for passive design to be an energy-efficient building solution, but it still provides thermal comfort. Research by Faheem et al. (2023) states that 83.3% of users want fresh air, which also explains the increase in window use and mosquito screens on windows. This is an alternative for architects who design buildings with maximum and optimal natural ventilation to reduce the use of air conditioning. However, there is a concern about whether AC is used with a natural ventilation system. This can force the AC thermostat to work continuously because outside air enters the room (Damiati et al., 2016). So, a strategy to minimize the use of AC by combining it with natural ventilation (mixed-mode) requires deeper management considerations so that they do not co-occur at the same time and in the same place, which has the potential to waste energy.

4.3.2 Adaptation through the use of fans

Behavioral adaptation using fans is also still the primary alternative for users. Fans are still an adaptation effort for users because of their needs regarding the speed of air flowing in the room. The average percentage of fan use from 9 studies was 32.5%. Table 11 shows the rate of fan use in each study. Users who predominantly use fans as a thermal adaptation are again found in China.

Table 11. The list of studies that discuss fans and their usage percentages

Reference	Location	Mode	Fan Usage (%)
Damiati et al. (2016)	Malaysia	FR	10
	Japan	FR	8
Guo et al. (2023)	China	ECA	68.6
		NV	93.8
KC et al., 2018	Japan	Overall	24.3
Aparicio-Ruiz et al. (2021)	Spain	NV	18
Zheng et al. (2022)	China	AC and fan	24,32
Rijal et al. (2019)	Japan	FR	28,2
Singh et al. (2017)	North-East India	NV	68
Song et al. (2017)	China	MM (lowest)	35
		MM (highest)	35
Yue & Zhongqing (2023)	Shaoxing, China	mixed-mode spring	13.1
		mixed-mode summer	73.6
		mixed-mode autumn	21.5
		mixed-mode winter	0.82

Several studies state that air velocity influences user adaptation to high temperatures (Indraganti et al., 2014; Wu et al., 2019; Rawal et al., 2022). Based on the research results of Rawal et al. (2022), for every 10ºC increase, the comfort requirement for air velocity increases by 0.55 m/s. Wu et al. (2019) also revealed the results of their research, which showed that 53% thought the use of fans was better for increasing air velocity indoors than the use of windows. According to previous findings, space users can adapt to high temperatures (de Dear et al., 2020), and one of the factors is that indoor air velocity meets user comfort. This shows that the air velocity aspect is worth considering when developing natural ventilation strategies. Good indoor airflow quality in a room has been proven to increase the user's thermal comfort range. The high percentage of windows and fans shows that the ventilation aspect through air circulation can be the main feature for users to adapt to thermal conditions. So, it is essential for a building to pay attention to wind direction to provide thermal comfort that is more energy efficient.

4.3.3 Adaptation to air conditioning

AC (air conditioning) also remains a user-adaptive behavior towards thermals. AC is equipment that can quickly adjust to the user's thermal needs. The flexibility offered by AC makes it often used, especially in tropical areas like Malaysia. Table 12 shows seven studies that found adaptation to AC use and the percentage of use in each study. The highest rate of AC use was found in Malaysia and Japan, with usage percentages above 25%, namely in research by Damiati et al. (2016), KC et al. (2018), Rijal et al. (2019), and Zaki et al., (2017).

Table 12. The list of studies that discuss air conditioning and its usage percentages

Reference	Location	Mode	AC Usage (%)
Damiati et al. (2016)	Malaysia	CL	47,5
	Indonesia	CL	17
	Japan	CL	5
KC et al. (2018)	Japan	CL	34,9
Aparicio-Ruiz et al. (2021)	Spain	AC	25
Rawal et al. (2022)	India	NV and MM (lowest)	1
		NV and MM (highest)	1
Rijal et al. (2019)	Japan	CL	27,7
Song et al. (2017)	China	MM (lowest)	16,3
		MM (highest)	16,3
Zaki et al. (2017)	Malaysia	CL	27
	Japan	CL	4

AC remains the choice in buildings with various ventilation features, even though the average use percentage is 18.6%. This shows that there is still an opportunity to make fans or windows the leading adaptation choice for building users who use various types of ventilation.

Apart from the function of AC, which is still a means of adaptation, AC was also found to cause overcooling, which was found in research by Zaki et al. (2017) and Damiati et al. (2016). In the case of research by Zaki et al. (2017), the high intensity of AC usage is because building users are students who feel irresponsible paying for electricity. In the case of Damiati et al. (2016), users reported feeling overcooling and adapted by opening the window so that warm air could enter the room. This impacts greater energy consumption because the AC continues to work even though the user has had enough until overcooling eventually occurs. This weakness is a gap in formulating good adaptation management regarding the schedule of AC use. These findings emphasize that AC must also be adjusted to the user's clothing's activity, character, and insulation.

Users are still dominant in adapting to features related to temperature settings and air conditions. Air velocity adjustment strategies have the potential to reduce AC energy loads. This is because many users of natural and mixed-mode ventilation buildings still need the comfort of air velocity and fresh air.

Figure 4 shows that the window and fan usage ranges are almost identical. The only difference lies in the average usage percentage and standard deviation, which shows higher and more varied window usage (Table 9). However, the similarity between window and fan usage ranges shows that air circulation can be an energy-saving strategy for creating comfortable spaces. In the case of using AC, the range of use and standard deviation are smaller compared to adaptations using windows and fans. Users have almost the same behavior when using AC. This also goes hand in hand with comfortable temperatures between users in AC rooms (tropical and non-tropical climates), which tend to be similar. AC creates a comfortable thermal space that is easy for every user to agree on. In contrast to the conditions of NV and MM rooms, users have different thermal comforts with varying adaptations, so a deep understanding of culture, psychology, and user activities in NV and MM rooms is needed.

The user's flexibility in determining clothing, window use, fans, air conditioning, and other adaptive behaviors is essential to the adaptive thermal comfort design strategy. Clothing that does not match the user's thermal preferences results in the user needing to adapt thermally in other ways. The window design should also be flexible and compelling so the user can use it easily. Building designs that prioritize air velocity and energy-efficient thermal adaptation are needed.

Other adaptation behaviors that are often used are space heaters and metabolic adaptation. These two behaviors have a smaller percentage of use compared to the behavior of using windows, fans, and AC in each study. Space heaters are often used in countries with cold climates, such as China and Japan. Metabolic adaptation users usually consume cold drinks or food, bathing, changing body position, and doing nothing (Guo et al., 2023; Zaki et al., 2017; Damiati et al., 2016). Metabolic adaptation is closely related to the user's flexibility in a room. User limitations in consuming cold drinks and food and limited user movement within the room can affect the user's thermal comfort level.

5. Conclusion

The adaptive thermal comfort approach can be a flexible solution that adapts to character, behavior, clothing, and climate. Using the right model accompanied by detailed thermal comfort calculations can avoid errors in determining thermal comfort. Many findings on comfortable temperatures that do not comply with applicable standards emphasize the importance of involving the user's parameters and various views in measuring thermal comfort.

Non-tropical climates show a wider range of thermal comfort. Building designers need to consider the importance of clothing and user culture. Natural ventilation buildings have the potential for energy efficiency to achieve thermal comfort with a wider temperature range. This can help natural ventilation building designers achieve thermal comfort due to consideration of user adaptation in determining comfortable temperatures.

NV and MM buildings in tropical climates also have higher thermal comfort than AC buildings. This can be an energy-saving design opportunity through natural ventilation that supports user adaptation. However, future research must examine how long thermal comfort lasts in natural ventilation and what air velocity is required. Further research can also maximize the potential of natural ventilation in mixed-mode building types to utilize air velocity to support thermal comfort. However, it still saves energy even though it synergizes with an artificial ventilation system.

The challenge in designing buildings in non-tropical climates is to identify a broader range of thermal comfort because the number of seasons is also more diverse. This is shown by the standard deviation of user temperature comfort in non-tropical climates (4.25), which is more significant than in tropical climates (1.98), both when it is not winter (2.95) and during winter (4.32).

There are opportunities for inclusive and collaborative design among users from various cultures. This is based on the closeness of users' thermal preferences in tropical and non-tropical non-winter climates. This proximity to thermal comfort also opens up opportunities for building design in tropical regions to accommodate users' preferences from various countries.

6. Acknowledgement

The authors thank the Indonesia Endowment Fund for Education (LPDP) and the Higher Education Financing Center (BPPT) for financing and supporting this research.

7. References

Alfano, F. R. d., Olesen, B. W., & Palella, B. I. (2017). Povl Ole Fanger's impact ten years later. Energy and Buildings, 152, 243–249. https://doi.org/10.1016/j.enbuild.2017.07.052

Allah, M.Z., Mohamed Kamar, H., Hariri, A., & Wong, K. Y. (2023, December). Investigating adaptive thermal comfort in office settings: A case study in Johor Bahru, Malaysia. Case Studies in Chemical and Environmental Engineering, 8, 100466. https://doi.org/10.1016/j.cscee.2023.100466

Aparicio-Ruiz, P., Barbadilla-Martin, E., Guadix, J., & Munuzuri, J. (2021). A field study on adaptive thermal comfort in Spanish primary classrooms during summer. Building and Environment, 203, 108089. https://doi.org/10.1016/j.buildenv.2021.108089

Barbadilla-Martín, E., Salmerón Lissén, J. M., Guadix Martín, J., Aparicio-Ruiz, P., & Brotas, L. (2017). Field study on adaptive thermal comfort in mixed mode office buildings in southwestern Spain. Building and Environment, 123, 163–175. https://doi.org/10.1016/j.buildenv.2017.06.042

Yadeta, C., Indraganti, M., Tucho, G. T., & Alemayehu, E. (2023). Study on adaptive thermal comfort model and behavioral adaptation in naturally ventilated residential buildings, Jimma Town, Ethiopia. Energy and Buildings, 298, 113483. https://doi.org/10.1016/j.enbuild.2023.113483

Damiati, S. A., Zaki, S. A., Rijal, H. B., & Wonorahardjo, S. (2016). Field study on adaptive thermal comfort in office buildings in Malaysia, Indonesia, Singapore, and Japan during hot and humid seasons. Building and Environment, 109, 208–223. https://doi.org/10.1016/j.buildenv.2016.09.024

de Dear, R., Kim, J., Candido, C., & Deuble, M. (2015). Adaptive thermal comfort in Australian school classrooms. Building Research & Information, 43(3), 383–398. https://doi.org/10.1080/09613218.2015.991627

de Dear, R., Xiong, J., Kim, J., & Cao, B. (2020). A review of adaptive thermal comfort research since 1998. Energy and Buildings, 214, 109893. https://doi.org/10.1016/j.enbuild.2020.109893

Enescu, D. (2017). A review of thermal comfort models and indicators for indoor environments. Renewable and Sustainable Energy Reviews, 79, 1353–1379. https://doi.org/10.1016/j.rser.2017.05.175

Faheem, M., Bhandari, N., & Tadepalli, S. (2023). Adaptive thermal comfort in naturally ventilated hostels of warm and humid climatic regions, Tiruchirappalli, India. Energy and Built Environment, 4(5), 530–542. https://doi.org/10.1016/j.enbenv.2022.04.002

Forcada, N., Gangolells, M., Casals, M., Tejedor, B., Macarulla, M., & Gaspar, K. (2021). Field study on adaptive thermal comfort models for nursing homes in the Mediterranean climate. Energy and Buildings, 252, 111475. https://doi.org/10.1016/j.enbuild.2021.111475

Guo, Y., Tang, H., Gao, Y., Wang, Y., Meng, X., Cai, G., Zhao, J., Dewancker, B. J., & Gao, W. (2023). Thermal comfort and adaptive behaviors in office buildings: A summer pilot study in Turpan (China). Heliyon, 9(10), e20646. https://doi.org/10.1016/j.heliyon.2023.e20646

Haddad, S., Osmond, P., & King, S. (2016). Application of adaptive thermal comfort methods for Iranian schoolchildren. Building Research & Information, 47(2), 173–189. https://doi.org/10.1080/09613218.2016.1259290

Indraganti, M., Ooka, R., Rijal, H. B., & Brager, G. S. (2014). Adaptive model of thermal comfort for offices in hot and humid climates of India. Building and Environment, 74, 39–53. https://doi.org/10.1016/j.buildenv.2014.01.002

Jiang, J., Wang, D., Liu, Y., Di, Y., & Liu, J. (2020). A field study of adaptive thermal comfort in primary and secondary school classrooms during the winter season in Northwest China. Building and Environment, 175(19), 106802. https://doi.org/10.1016/j.buildenv.2020.106802

Jiao, Y., Yu, H., Yu, Y., Wang, Z., & Wei, Q. (2020). Adaptive thermal comfort models for homes for older people in Shanghai, China. Energy and Buildings, 215, 109918. https://doi.org/10.1016/j.enbuild.2020.109918

Karyono, K., Abdullah, B. M., Cotgrave, A. J., & Bras, A. (2020). The adaptive thermal comfort review from the 1920s, the present, and the future. Developments in the Built Environment, 4, 100032. https://doi.org/10.1016/j.dibe.2020.100032

KC, R., Rijal, H., Shukuya, M., & Yoshida, K. (2018). An in-situ study on occupants' behaviors for adaptive thermal comfort in a Japanese HEMS condominium. Journal of Building Engineering, 19, 402–411. https://doi.org/10.1016/j.jobe.2018.05.013

Khalid, W., Zaki, S. A., Rijal, H. B., & Yakub, F. (2019). Investigation of comfort temperature and thermal adaptation for patients and visitors in Malaysian hospitals. Energy and Buildings, 183, 484–499. https://doi.org/10.1016/j.enbuild.2018.11.019

Liu, J., Yu, W., & Cai, T. (2020). Field Study on Adaptive Thermal Comfort in Coastal Buildings in China. Journal of Coastal Research, 111(sp1). https://doi.org/10.2112/jcr-si111-040.1

López-Pérez, L., Flores-Prieto, J., & Ríos-Rojas, C. (2019). Adaptive thermal comfort model for educational buildings in a hot-humid climate. Building and Environment, 150, 181–194. https://doi.org/10.1016/j.buildenv.2018.12.011

Mishra, A. K., & Ramgopal, M. (2015). An adaptive thermal comfort model for the tropical climatic regions of India (Köppen climate type A). Building and Environment, 85, 134–143. https://doi.org/10.1016/j.buildenv.2014.12.006

Mohammadpourkarbasi, H., Jackson, I., Nukpezah, D., Addo, I. A., & Oppong, R. A. (2022). Evaluation of thermal comfort in library buildings in the tropical climate of Kumasi, Ghana. Energy and Buildings, 268, 112210. https://doi.org/10.1016/j.enbuild.2022.112210

Nicol, J. F., & Humphreys, M. A. (2002). Adaptive thermal comfort and sustainable thermal standards for buildings. Energy and Buildings, 34(6), 563–572. https://doi.org/10.1016/s0378-7788(02)00006-3

Parkinson, T., de Dear, R., & Brager, G. (2020). Nudging the adaptive thermal comfort model. Energy and Buildings, 206, 109559. https://doi.org/10.1016/j.enbuild.2019.109559

Rawal, R., Shukla, Y., Vardhan, V., Asrani, S., Schweiker, M., de Dear, R., . . . Somani, G. (2022). Adaptive thermal comfort model based on field studies in five climate zones across India. Building and Environment, 219, 109187. https://doi.org/10.1016/j.buildenv.2022.109187

Rijal, H., Humphreys, M., & Nicol, F. (2015). Adaptive Thermal Comfort in Japanese Houses during the Summer Season: Behavioral Adaptation and the Effect of Humidity. Buildings, 5(3), 1037–1054. https://doi.org/10.3390/buildings5031037

Rijal, H. B., Humphreys, M. A., & Nicol, J. F. (2017). Towards an adaptive model for thermal comfort in Japanese offices. Building Research & Information, 45(7), 717–729. https://doi.org/10.1080/09613218.2017.1288450

Rijal, H. B., Humphreys, M. A., & Nicol, J. F. (2019). Adaptive model and the adaptive mechanisms for thermal comfort in Japanese dwellings. Energy and Buildings, 202, 109371. https://doi.org/10.1016/j.enbuild.2019.109371

Rupp, R. F., de Dear, R., & Ghisi, E. (2018). Field study of mixed-mode office buildings in Southern Brazil using an adaptive thermal comfort framework. Energy and Buildings, 158, 1475–1486. https://doi.org/10.1016/j.enbuild.2017.11.047

Rupp, R. F., Vásquez, N. G., & Lamberts, R. (2015). A review of human thermal comfort in the built environment. Energy and Buildings, 105, 178–205. https://doi.org/10.1016/j.enbuild.2015.07.047

Singh, M. K., Ooka, R., Rijal, H. B., Kumar, S., & de Dear, R. (2023). Adaptive thermal comfort in the offices of three climates of North-East India. Journal of Building Engineering, 75, 106843. https://doi.org/10.1016/j.jobe.2023.106843

Singh, M. K., Ooka, R., Rijal, H. B., & Takasu, M. (2017). Adaptive thermal comfort in the offices of North-East India in the autumn season. Building and Environment, 124, 14–30. https://doi.org/10.1016/j.buildenv.2017.07.037

Song, W. F., Zhang, C. J., Lai, D. D., Wang, F. M., & Kuklane, K. (2016). Use of a novel, innovative heating sleeping bag to improve wearers' local thermal comfort in the feet. Scientific Reports 6. https://doi.org/10.1038/srep19326

Takasu, M., Ooka, R., Rijal, H. B., Indraganti, M., & Singh, M. K. (2017). Study on adaptive thermal comfort in Japanese offices under various operation modes. Building and Environment, 118, 273–288. https://doi.org/10.1016/j.buildenv.2017.02.023

Thapa, S., Bansal, A. K., & Panda, G. K. (2017). Adaptive thermal comfort in the residential buildings of northeast India—An effect of elevation difference. Building Simulation, 11(2), 245–267. https://doi.org/10.1007/s12273-017-0404-x

Trebilcock, M., Soto-Muñoz, J., Yañez, M., & Figueroa-San Martin, R. (2017). The right to comfort: A field study on adaptive thermal comfort in free-running primary schools in Chile. Building and Environment, 114, 455–469. https://doi.org/10.1016/j.buildenv.2016.12.036

Vergés, R., Gaspar, K., & Forcada, N. (2023). Assessment of the energy implications adopting adaptive thermal comfort models during the cooling season: A case study for Mediterranean nursing homes. Energy and Buildings, 299, 113598. https://doi.org/10.1016/j.enbuild.2023.113598

Williamson, T., & Daniel, L. (2020). A new adaptive thermal comfort model for homes in temperate climates of Australia. Energy and Buildings, 210, 109728. https://doi.org/10.1016/j.enbuild.2019.109728

Wu, Z., Li, N., Wargocki, P., Peng, J., Li, J., & Cui, H. (2019). Adaptive thermal comfort in naturally ventilated dormitory buildings in Changsha, China. Energy and Buildings, 186, 56–70. https://doi.org/10.1016/j.enbuild.2019.01.029

Xu, C., Li, S., Zhang, X., & Shao, S. (2018). Thermal comfort and thermal adaptive behaviours in traditional dwellings: A case study in Nanjing, China. Building and Environment, 142, 153–170. https://doi.org/10.1016/j.buildenv.2018.06.006

Yau, Y., & Chew, B. (2014). Adaptive thermal comfort model for air-conditioned hospitals in Malaysia. Building Services Engineering Research and Technology, 35(2), 117–138. https://doi.org/10.1177/0143624412474829

Yue, L., & Zhongqing, C. (2023). Seasonal thermal comfort and adaptive behaviours for the occupants of residential buildings: Shaoxing as a case study. Energy and Buildings, 292, 113165. https://doi.org/10.1016/j.enbuild.2023.113165

Zaki, S. A., Damiati, S. A., Rijal, H. B., Hagishima, A., & Abd Razak, A. (2017). Adaptive thermal comfort in university classrooms in

Malaysia and Japan. Building and Environment, 122, 294–306. https://doi.org/10.1016/j.buildenv.2017.06.016

Zheng, P., Wang, C., Liu, Y., Lin, B., Wu, H., Huang, Y., & Zhou, X. (2022). Thermal adaptive behavior and thermal comfort for occupants in multi-person offices with air-conditioning systems. Building and Environment, 207, 108432. https://doi.org/10.1016/j.buildenv.2021.108432

Zheng, W., Shao, T., Lin, Y., Wang, Y., Dong, C., & Liu, J. (2022). A field study on seasonal adaptive thermal comfort of the elderly in nursing homes in Xi'an, China. Building and Environment, 208, 108623. https://doi.org/10.1016/j.buildenv.2021.108623

Zhou, H., Yu, W., Zhao, K., Shan, H., Zhou, S., Zhang, Y., . . . Wei, S. (2024). Adaptative thermal comfort analysis in the elderly based on Fried frailty classification in residential buildings during summer. Building and Environment, 252, 111262. https://doi.org/10.1016/j.buildenv.2024.111262