



## Review

# A Review of Thermal Comfort in Residential Buildings: Comfort Threads and Energy Saving Potential

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**Abstract:** Residential buildings instigate a vital role in creating a safe and comfortable indoor living environment. The phenomenon of overheating, an impact of climate change, can cause a negative effect on residents' productiveness and heat-related illnesses and can even force high pressure on electricity generation by increasing the risk of power outages due to excessive peak cooling and heating requirements. Various issues on building thermal comfort are being evolved and discussed in review articles. However, there are few articles that review the current condition of adaptive thermal comfort studies and the potential for energy savings in residential buildings. Therefore, the aims for this paper are to: identify comfort temperature ranges in residential buildings, investigate the correlation of comfort temperature with indoor and outdoor temperatures with the aid of 'comfort threads', and clarify the effect of adaptive measures on residential energy saving potential. This study obtained a large variation of residential comfort temperatures, which mostly depend on the climate and operation modes of the building. 'Comfort threads' explains that people are adapting to a large variation of indoor and outdoor temperatures and the wide range of comfort temperature could provide significant energy savings in residential buildings. This review provides insight on and an overview of thermal comfort field studies in residential buildings.

**Keywords:** thermal comfort; residential building; comfort temperature; adaptive model; energy saving



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## 1. Introduction

Thermal comfort has been a notable issue toward achieving Sustainable Development Goals (SDGs) 3, 7 and 11, which aim for “good health and well-being”, “affordable and clean energy” and “sustainable cities and communities”. It has been described as the satisfaction perception of how a person feels in the surrounding thermal environment [1]. Thermal comfort is the condition of mind that describes the satisfaction rate of the thermal condition [2]. Air temperature, radiant temperature, relative humidity, air velocity, metabolic rate, and clothing insulation are all closely attributed to thermal comfort. Therefore, any changes in these variables can have an impact on human thermal comfort.

Residential buildings are being known as a dominant place for resting. The thermal comfort level in residential buildings has a great impact on the emotional and physical of the residents. For example, high temperature or overheating in the dwelling can create to various problem (sweating, tiredness, skin allergies). Therefore, the acceptable and comfortable indoor environment should be considered to improve the resident's emotion, health, and well-being [3].

### 1.1. The Residential Comfort Temperature

Previous studies focus on residential building while conducting field measurements and surveys to predict how individuals will respond in a certain situation and at which

temperature they will feel comfortable. These temperatures are commonly referred to as ‘comfort temperature’ or ‘neutral temperature’. Han et al. [4] discovered that 90% of residents accepted an indoor air temperature from 22.0–25.9 °C. Gong et al. [5] researched the possible correlations between the occupants’ thermal sensations to on-site environmental monitoring under natural ventilation and identified 20.9–27.5 °C (summer) and 12.2–20.1 °C (winter) as comfort temperatures. Yu et al. [6] found the acceptable indoor comfort temperature range to be 10.2–22.9 °C, and Rijal et al. [7] concluded 25.6 °C (summer) and 19.8 °C (winter) as the mean comfort temperatures. The range of comfort or acceptable environment for the occupants is often wider in residential buildings rather than in offices [8,9] or in educational [10,11] or hospital buildings [12,13]. This might be due to various thermal comfort requirements, less predictable activities, and more ways to adapt to the existing thermal environment [14].

In addition, in a study of high-altitude residential buildings in India, Thapa [15] determined the comfort temperature did not comply with the ASHRAE standard and thus proposed a new comfort zone for regions with a similar cold climate. In 2018, KC et al. [16] collected 17,026 votes to conduct a survey on occupants’ behavior for adaptive thermal comfort in a Japanese condominium. Ozarisooy and Altan [17] conducted field surveys in 288 flats of a social housing estate in Cyprus to predict individual aspects of adaptive thermal comfort and influences on its validity in purpose built residential tower blocks. Liu et al. [18] revealed the significance of seasonal variation on comfort temperature in China with a difference of 3.3 °C for summer and winter, and a 2.7 °C difference for the spring and autumn seasons. Therefore, the significance of regional, seasonal, and climatic conditions of the buildings on the comfort temperature are important to be discussed.

The same indoor or outdoor conditions may lead to different subjective responses. One obvious reason is that people differ and therefore not all are satisfied by the same conditions. In a tropical climate, indoor and outdoor air temperatures stay as the major climatic factors that can have an impact on the thermal comfort condition [19]. In China, the comfort temperature of 25.4 °C inside the residences has been determined when the outdoor temperature ranges from 10.7 to 31.7 °C [20]. By focusing mainly on comparing the occupant’s rating of thermal comfort and the implementation of adaptive approaches in two different climates, Jeong et al. [21] concluded that the varying range of climates in Australia could indicate that people have different ranges of thermal acceptability and tolerance. Other than that, Rijal et al. [7] proposed an adaptive model for highly insulated Japanese dwellings and evaluated the differences of seasonal variation in comfort temperature. They mentioned that the comfort temperature and its seasonal range depend on the climate and building design, which resulted to 23.0, 26.8 and 20.2 °C as the comfort temperatures for different operation modes of free running, cooling, and heating, respectively. Thus, there is a need to understand how comfort temperature varies or differs in different ranges of indoor and outdoor temperatures.

### 1.2. Ideation of ‘Comfort Threads’

Most thermal comfort studies that conducted field surveys have measured and collected the data of indoor and outdoor temperatures, while gathering the information and thermal comfort votes from the respondents. Therefore, the relationship of comfort temperature with indoor and outdoor temperatures have been discussed over the years. Plotting the indoor comfort temperature data against the indoor and outdoor temperatures can be one of the methods to illustrate the relationship between them. From the regression equation in each study, these data can be formed as a line. These lines are called ‘comfort threads’ in this study. The length and slope of the lines reflect the temperatures to which they were valid and the sensitivity of the residents to the temperature change, respectively. Comfort threads can illustrate how the comfort temperature varies according to different ranges of indoor and outdoor air temperatures. Once plotted, the indoor comfort temperature can then be estimated depending on the indoor and outdoor temperatures that were collected and measured during the field survey. The idea for ‘comfort threads’

is from the article of Nicol [22] and Nicol et al. [23], where the ‘temperature cloud’ were discussed. Temperature cloud was described as the data of indoor temperature and outdoor temperature simultaneously against each other [22]. The study has identified a wide range of indoor temperature in dwellings, which was identified as an adaptive response to indoor environments and thus led the interest of ‘comfort threads’.

### *1.3. Energy Saving Potential from Thermal Comfort Adaptive Measures*

The residential and service sectors account for more than one third of world energy consumption and approximately 40% of the total carbon dioxide (CO<sub>2</sub>) emissions [24]. As a result, these sectors are anticipated to minimize their energy consumption and CO<sub>2</sub> emissions. Without improvements to the existing policies, the supply and demand for energy consumption will increase by 1.3% per year until 2040 [25]. In order to provide a comfortable and acceptable indoor environment, the heating, ventilation, and air-conditioning (HVAC) systems account for at least 50% from building energy [26]. This can be supported by Barreca et al. [27] who found that by using AC (air conditioning) the average residential electricity use tends to rise by 11%. In addition, AC greenhouse gas emissions will contribute to a 0.5 °C increase in global temperatures [28]. According to Chang et al. [29], consumption of energy for heating has been steadily increasing with the development of the building sector and the importance placed on the indoor environment. This can significantly affect energy consumption. A person can freely change the indoor temperature from mechanical cooling or adapt themselves to the environment more freely in residential buildings as it is not a must for them to follow any requirement from other people. Therefore, adaptive thermal comfort is important in order to understand the perception of residents and how it can contribute to the energy saving potential.

### *1.4. Research Gap and Objectives*

Over time, several review papers on thermal comfort studies have evolved and discussed many issues on thermal comfort. Most of the review articles generally focus more on the development of adaptive thermal comfort models [30,31], issues of individual difference [32,33], the balance between energy efficiency and thermal comfort [34], and the discussions were based on multiple building types, such as offices, hospitals, and educational and residential buildings. Therefore, review articles of thermal comfort studies that focus on one specific building, which can have more in-depth discussion, comprehensive and systematic literature, are continuing to increase in number of publications.

Recently, Zomorodian et al. [35] reviewed 48 papers of field survey studies in educational buildings and compared the thermal comfort condition in different climate, educational stage, and thermal comfort approach. Singh et al. [36] proposed adaptive comfort equations and highlighted the gaps in the classroom comfort studies by reviewing 93 articles. Another review article studied the insight on the future and current status of thermal comfort studies in hospital buildings based on different functional areas and people [37]. For office buildings, one review article investigated the thermal comfort developments with respect to the concept of comfort in office buildings over the last 10 years and highlighted possible topics that need further analysis [38]. However, there is a limited availability of review papers that considered and justified the current state for residential adaptive thermal comfort studies and the potential of energy saving. More specifically, the questions addressed in this paper are:

1. What are the comfort temperatures in residential buildings of different operation modes and climates?
2. How can ‘comfort threads’ portray the relationship of residential comfort temperature with indoor and outdoor air temperature?
3. What are the impacts of residential building adaptations to energy consumption?

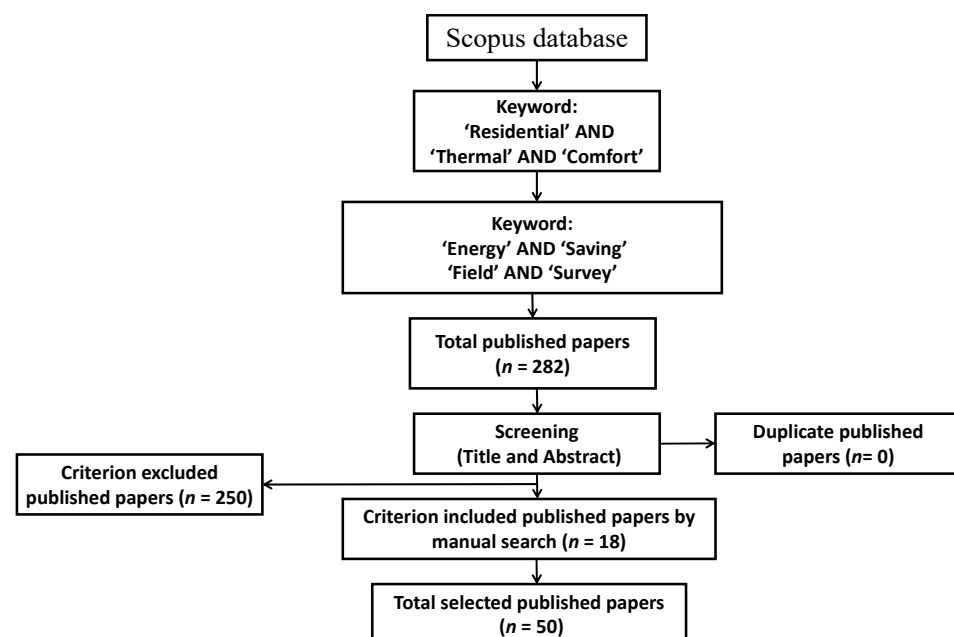
Thus, this paper investigates and reviews various thermal comfort field studies in residential buildings from different countries, climates, types of buildings and operation modes. The objectives are to: identify the comfort temperature ranges in residential buildings;

investigate the correlation of comfort temperature with indoor and outdoor air temperature; investigate the relationship between thermal sensation vote with indoor air temperature; and clarify the effect of adaptive measures on residential energy saving potential.

## 2. Methodology

### 2.1. Process of Research Methodology

A systematic review was conducted by using the combination of ('residential' AND 'thermal' AND 'comfort'). Then, within the result a combination of terms ('energy' AND 'saving') and ('field' AND 'survey') were used to search for the published papers required for this study. A total of 282 published papers were obtained from the keyword search as shown in Figure 1. By screening the title and abstract from the downloaded csv file of the obtained results, 250 published papers were excluded based on several criteria. There are five criteria of the inclusion and exclusion of the published papers in this study. For inclusion, papers (1) conducted field survey and measurement of thermal comfort in residential building; (2) provided regression and adaptive comfort equation, and (3) addressed the issue of residential energy implication by thermal comfort adaptation. Excluded papers were (4) publications other than in journals, conferences, and reviews, and (5) publications in languages other than English. Moreover, 18 published papers were identified by manual search as they could have some contribution that was well aligned with this study. No published paper was excluded due to duplication as only the Scopus database was used in this study. The results were then refined, and all inclusion and exclusion criteria were considered, which resulted to 50 published papers.



**Figure 1.** Systematic review process ( $n$  is the number of published papers).

### 2.2. Calculation of Comfort Temperature

The relationship between the thermal sensation vote ( $TSV$ ) and thermal indices, such as indoor temperature, globe temperature, and operative temperature, can be determined by using linear regression method. The linear regression of  $TSV$  based on the ASHRAE's scale (+3 to −3) or (1 to 7) were being used to calculate the comfort temperature based on the range of indoor temperature. The comfort temperature can be calculated by using Equation (1).

$$TSV = aT_i + b \quad (1)$$

where  $T_i$  represents several thermal indices of indoor temperature for example, indoor air, operative, globe, or radiant temperatures,  $a$  is the slope of the line and  $b$  refers to the

value of  $TSV$  when  $T$  is 0. By substituting neutral condition (4 or 0) in Equation (1), the comfort temperature can be calculated. Other than that, the comfort temperature can be predicted by using Griffiths' method when there is no information of linear equation. An estimation relationship between comfort vote and temperature can be determined by Griffiths method when the predicted comfort temperature is made for each comfort vote. This relationship can be shown in Figure 2 [39,40]. Both comfort and neutral temperatures are indicated by  $T_c$ . Due to thermal adaption, buildings styles and depending on the seasons, comfort temperature could be diverse [6]. Equation (2) shows the calculation of  $T_c$  by Griffiths method.

$$T_c = T_i + \frac{(0 - TSV)}{\alpha} \quad (2)$$

'0' indicates the condition of comfortable or neutral, therefore, it can be changed by '4' when a seven-point thermal sensation scale (1 to 7) was applied.  $\alpha$  represents Griffiths constant, which can also be represented by the regression coefficient. A value of 0.5 was chosen as the value for  $\alpha$  [7]. As the Griffiths constant or the thermal sensitivity level of the resident is being assumed, the comfort temperature can be determined without a large amount of data.

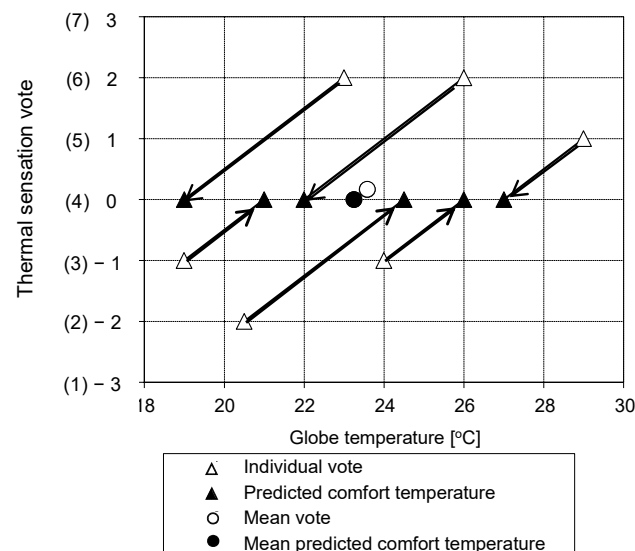


Figure 2. Griffiths method for regression coefficient of 0.5.

### 3. Results and Discussion

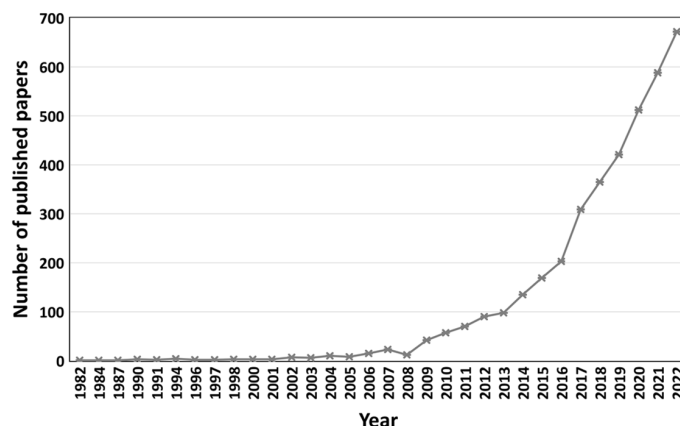
#### 3.1. Overview of Previous Published Papers

Previous publications that related to thermal comfort in residential buildings can be searched in the Scopus database by using the topic search of 'thermal comfort', then within the results, the terms of 'residential', 'measurement' and 'comfort temperature' were used to find any related papers from the titles, abstract and keywords. The total published papers on residential thermal comfort studies have continued to rise and have shown an increasing trend at which approximately 3837 papers were identified and presented in Figure 3. The increased number of published papers is significant as the publications after 2016 contribute approximately 80% from all published papers that were identified. This suggests that people are more interested in thermal comfort in residential buildings.

#### 3.2. Publication's Keyword Analysis

VOSviewer, which was introduced by Van Eck and Waltman [41], was used as the tool for bibliometric review to produce a network visualization map and clustered co-occurrences keywords. The keywords of the 282 published papers were analyzed by using VOSviewer. All the words were extracted from the title and abstract of the previous articles, and they were filtered for a minimum 20 co-occurrences. With filtered words, the most

relevant keywords were extracted through a VOSviewer built-in text mining function [42]. With the list of the keywords, VOSviewer generated the co-occurrence map and clustered the keywords based on how many times they re-occurred. The network visualization map illustrates the clusters in colors based on similarity and relation to each other along with lines connecting nodes within the clusters. The closer the authors are to each other, the stronger the relationship they have in the research being conducted. In this study, 21 terms occurred at least 20 times.



**Figure 3.** Overview of previous published papers for residential thermal comfort studies.

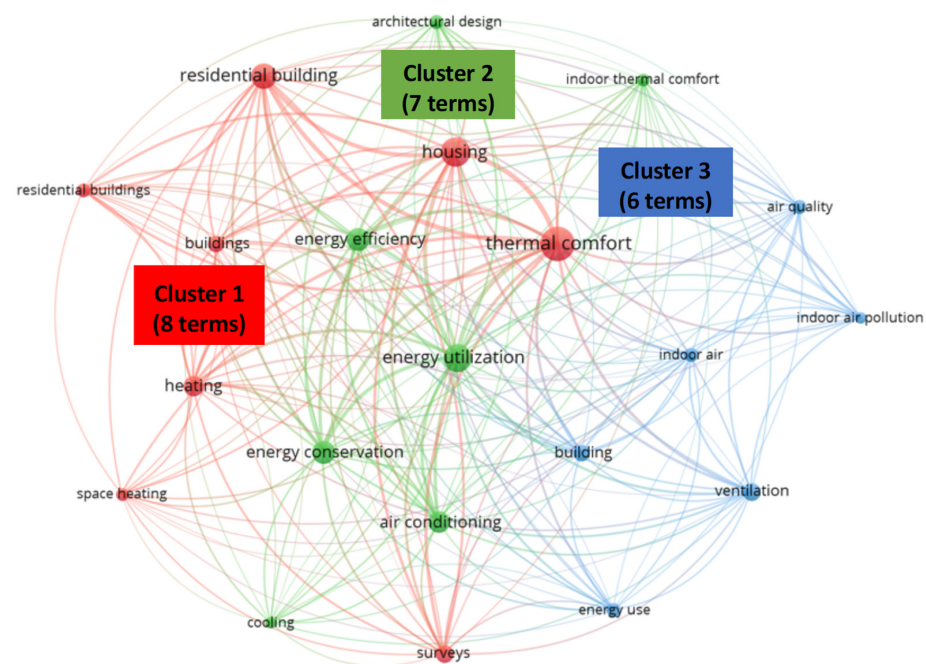
Figure 4 illustrates the result for network visualization at which three clusters can be determined. Cluster 1 (red color) which consists of 8 terms highlighted a strong link of ‘thermal comfort’ with ‘housing’, ‘residential building’ and ‘surveys’. This attracts interest in investigating people’s perception of their thermal indoor environment especially, in their own home and the specific comfort temperature within different climates. Cluster 2 (green color) consists of 7 terms, which have a strong link of ‘energy utilization’ with ‘architectural design’, ‘cooling’ and ‘energy conservation’. As mentioned by Chiang et al. [43], shifting from the traditional fixed thresholds to adaptive energy demand could have at least a 20% drop in heating demand and an approximately 80% drop for cooling demand. Therefore, it is important to find other ways that can be adapted to provide energy saving potential in residential buildings. Lastly, in cluster 3 (blue color), there are 6 terms that show a strong link of ‘ventilation’ with ‘indoor air’ and ‘air quality’. It is known that adequate ventilation is essential for the health and comfort of building occupants, and the choice of ventilation system ultimately depends on indoor air quality requirements, heating and cooling loads, and also outdoor climate [44]. Thus, it is interesting to provide clarification on how comfort temperature is related to indoor and outdoor temperatures. Based on the three different colors of clusters that related to each other, three themes form the focus of this review article:

1. Variations of comfort temperature in residential buildings;
2. Comfort temperature related to different ranges of indoor and outdoor temperatures;
3. Energy saving potential in residential buildings based on thermal comfort.

### 3.3. Variations of Outdoor and Indoor Temperatures

Complaints about the indoor environment are often associated with temperature and humidity. Moreover, the residential environment can have a major role in providing shelter from extreme weather conditions. The relationship between indoor and outdoor temperatures can be observed from many previously published papers. One of the earliest articles appraised the issue of how enclosing buildings can change outdoor climatic factors in order to create an indoor environment [45]. The relationship between indoor and outdoor air temperature in Tokyo has been clarified. It was found that when the outdoor air temperature was low, the indoor air temperature distribution fell into two groups, where the indoor temperature for one of the dwellings was higher than the other dwelling [23].





**Figure 4.** Network visualization by VOSviewer (Clusters of the keywords co-occurrences).

Therefore, Table 1 contains data from past studies from which we have extracted all interesting points that can be tabulated, including from the data of indoor and outdoor air temperatures. Some of the studies did not provide the average data for indoor and outdoor temperatures, and thus we calculated average value by picking 10 different values from the related graph and finding the approximate mean value. Even though the sample size for each published paper was not the same, the regression analysis is useful for a rough estimation. Humphreys [46,47] and de Dear and Brager [48] also used different sample sizes in their regression analysis. From Table 1, ‘mixed’ mode is defined as the implementation of natural ventilation or a free running building with the use of other heating or cooling devices during the measurement period. This includes all mechanical cooling and heating systems or any other specific traditional method to maintain the preferred thermal environment. For instance, the residents of extreme cold climate in Nepal usually treated the kitchen area as the ‘heating room’, where the indoor temperature when they were cooking and the heating could be raised to 10–25 °C when the indoor temperature in any other ‘unheated room’ was almost continuously recorded as −0.3 °C throughout the whole day [49]. In terms of operation modes, KC et al. [16] conducted a field survey and investigated the aspect of residents’ behavior for adaptive thermal comfort in 47 Japanese condominiums. They found that indoor air temperature was highly correlated with outdoor air temperature in free running (FR) mode. In cooling (CL) mode, the mean indoor air temperature was 27.3 °C and in heating (HT) mode it was found that indoor air temperature was maintained at approximately 20 °C. Then, we collected the average data for outdoor and indoor air temperatures, which is provided in Table 1, and we present the correlation between indoor and outdoor temperatures as shown in Figure 5. It can be seen that when the outdoor temperature was below 10 °C, most of the case studies recorded a higher indoor air temperature with ranges from 14–24 °C. This might be due to the residents who were using their heating systems or passive controls to achieve the given temperature. A similar result from Lee and Lee [50] also showed that when the outdoor temperature was lower than 15 °C, the indoor temperature was maintained between 20 and 25 °C. For this relationship, the regression equation is:

$$T_i = 0.547T_o + 12.5 \quad (n = 65, R^2 = 0.72, S.E. = 0.04, p < 0.001) \quad (3)$$

**Table 1.** Previous thermal comfort field measurement studies.

Country	Climate	Reference	Sampling Period	No. of Houses	Variable Used	Operation Mode	$T_{oav}$ (°C)	$T_{omin}$ (°C)	$T_{omax}$ (°C)	$T_{iav}$ (°C)	$T_{imin}$ (°C)	$T_{imax}$ (°C)	$T_c$ (°C)
China	Continental	Yu et al. [6]	113 days	527	$T_{op}$	CL	7.0	−20	32.5	22.0	13.5	30.0	21.8
						HT	7.0	−20	32.5	12.5	0.5	24.0	14.5
	CB	Li et al. [51]	6 years	825	$T_g$	Mixed	-	-	-	16.0	12.0	20.0	24.3
	Continental	Yin et al. [52]	3 months	34	$T_g$	HT	3.3	-	-	22.7	-	-	22.5
	Temperate	Song et al. [20]	191 days	43	$T_{in}$	Mixed	21.3	10.7	31.7	24.1	-	-	25.4
			6 days	-	$T_{op}$	FR (SM)	27.3	-	-	29.6	-	-	28.0
	Temperate	Xu et al. [53]	9 days	-	$T_{op}$	FR (WT)	2.4	-	-	10	-	-	15.8
						FR (SP)	21.9	-	-	24.0	-	-	17.9
	Continental	Wei et al. [54]	1 year	156	$T_{op}$	FR (SM)	28.5	-	-	30.1	-	-	26.1
						FR (AU)	14.8	-	-	19.8	-	-	25.2
						FR (WT)	7.2	-	-	21.0	-	-	17.4
	Continental	Wang [55]	1 month	66	$T_{op}$	FR	-	-	-	20.1	-	-	21.4
	Tropical	Han et al. [4]	1 year	26	$T_{op}$	Mixed	33.0	30.5	35.5	29.8	24.6	34.6	28.6
			61 days			CL (SM)	18.9	8.1	28.2	30.0	26.5	33.3	24.2
	Sub-tropical	Gong et al. [5]	42 days	144	$T_{op}$	HT (WT)	-	-	-	16.1	10.4	22.8	16.2
	Continental	Yang et al. [56]	4 months	20	$T_{in}$	Mixed (WT)	2.0	−1.0	5.0	14.0	2.0	20.0	18.9
						FR (SM)	19.0	16.0	21.0	22.0	17.0	27.0	23.3
	Temperate	Yan et al. [57]	68 days	93	$T_{op}$	CL	32.6	22.5	41.1	27.7	22.3	32.6	28.7
						FR	30.2	21.8	39.3	29.6	26.7	34.5	26.9
						Mixed	31.5	21.8	41.1	28.6	22.3	34.5	27.7
Malaysia	Tropical	Djamila et al. [58]	1 year	-	$T_{in}$	FR	-	-	-	30.7	26.5	35.3	30.2
Indonesia	Tropical	Sujatmiko et al. [59]	6 months	5	$T_{in}$	Mixed	23.5	13.0	36.0	27.5	24.2	31.0	25.1
						Mixed	27.8	21.0	37.0	29.2	21.8	35.2	26.6
Ecuador	Temperate	Mino-Rodriguez et al. [60]	21 days	138	$T_{op}$	FR (LA)	16.4	8.8	26.9	23.4	-	-	23.6
						FR (MA)	15.0	9.9	23.6	22.4	-	-	22.5
						FR (HA)	12.6	7.9	20.8	20.1	-	-	19.8
Mexico	Temperate	Zepeda-Gil and Natarajan [61]	11 months	26	$T_{op}$	FR (SM)	14.8	4.1	30.0	20.5	10.8	37.5	19.8
						Mixed (WT)	10.4	−3.9	25.0	17.6	4.5	34.9	22.1
						FR (SP)	15.3	6.6	26.9	21.5	13.1	35.4	20.7
						Mixed (AU)	12.2	−4.7	24.8	18.7	4.3	33.0	20.8
Cyprus	Sub-tropical	Ozarisoy and Altan [17]	38 days	100	$T_{op}$	Mixed	32.1	23.7	36.0	30.6	25.4	34.1	28.5
Chile	Temperate	Pérez-Fargallo et al. [62]	7 months	40	$T_g$	Mixed	8.5	5.5	11.5	23.0	12.0	26.0	18.0
Nepal	CB	Rijal et al. [63]	40 days	36	$T_g$	FR (SM)	22.0	-	-	23.3	-	-	25.6
	Polar	Rijal [49]	7 days	9	$T_g$	Mixed (WT)	9.6	-	-	12.3	-	-	18.8
						Mixed	−3.1	-	-	7.8	-	-	10.7



Table 1. Cont.

Country	Climate	Reference	Sampling Period	No. of Houses	Variable Used	Operation Mode	$T_{oav}$ (°C)	$T_{omin}$ (°C)	$T_{omax}$ (°C)	$T_{iav}$ (°C)	$T_{imin}$ (°C)	$T_{imax}$ (°C)	$T_c$ (°C)
Nepal	CB	Shahi et al. [64]	5 days	3	$T_g$	Mixed (C)	12.0	10.0	14.0	10.9	-	-	17.2
						Mixed (T)	14.7	11.3	18.0	18.0	-	-	20.9
						Mixed (ST)	19.0	16.0	22.0	20.0	-	-	21.7
	CB	Gautam et al. [65]	24 days	108	$T_g$	Mixed (C)	11.4	4.0	18.0	12.2	-	-	13.8
						Mixed (T)	21.3	13.0	27.0	16.9	-	-	17.9
						Mixed (ST)	25.7	17.0	32.0	22.2	-	-	23.1
Japan	Temperate	Rijal et al. [66]	4 years	120	$T_g$	FR	18.9	-	-	23.5	-	-	23.9
						CL	27.6	-	-	27.6	-	-	27.1
						HT	7.2	-	-	19.6	-	-	19.4
	Temperate	Rijal et al. [67]	1 year	30	$T_g$	FR	18.8	-	-	22.7	-	-	22.7
						CL	28.9	-	-	28.0	-	-	27.1
						HT	6.7	-	-	17.7	-	-	18.9
	Temperate	Rijal et al. [7]	1 year	69	$T_{in}$	FR	16.8	-	-	23.1	-	-	23.0
						CL	27.4	-	-	27.3	-	-	26.8
						HT	8.3	-	-	19.9	-	-	20.2
India	Tropical	Thapa and Indraganti [68]	12 months	5	$T_{op}$	CL	26.4	18.5	31.3	28.2	22.4	35.1	28.3
						FR	15.5	5.7	24.0	18.9	9.0	26.9	19.4
						FR	17.8	5.7	31.3	20.9	9.0	35.1	21.3
	Tropical	Malik and Bardhan [69]	4 months	-	$T_g$	Mixed (MS)	26.1	24.3	28.3	28.5	26.9	30.5	28.3
						Mixed (WT)	24.9	23.1	27.5	27.4	24.8	30.8	28.3
						Mixed (SM)	29.7	29.1	31.4	31.8	29.4	33.8	28.3
	Tropical	Thapa et al. [70]	1 year	6	$T_{op}$	FR (LA)	18.7	8.3	25.6	20.0	13.7	25.1	20.6
						Mixed (HA)	11.5	1.3	20.8	17.2	9.1	22.1	17.4
						FR (CB)	15.1	1.3	25.6	18.6	9.1	25.1	18.9
	Tropical	Thapa [15]	1 year	5	$T_{op}$	Mixed	5.4	-1.1	12.2	15.5	9.1	21.4	15.5
						FR	13.8	6.2	18.0	18.1	14.1	22.1	18.3
						Mixed (WT)	22.3	12.1	32.6	21.3	14.4	30.5	25.6
	Tropical	Dhaka et al. [71]	2 years	30	$T_{in}$	Mixed (M)	31.3	21.6	37.0	28.9	19.5	33.8	27.0
						Mixed (SM)	34.0	25.7	45.1	31.8	26.2	39.1	29.4
Nigeria	Tropical	Adaji et al. [72]	1 month	8	$T_g$	Mixed	31.1	23.5	41.1	31.7	29.1	34.1	29.6
						Mixed	30.3	23.0	38.4	33.6	31.0	36.4	28.2
Madagascar	Sub-tropical	Nematchuoa et al. [73]	1 year	67	$T_{in}$	FR	26.8	20	33.5	26.0	20.5	31.5	24.5
Ethiopia	Tropical	Yadeta et al. [74]	120 days	104	$T_g$	Mixed	20.1	13.2	23.6	26.4	18.0	33.0	20.4

$T_{oav}$ : Average outdoor temperature;  $T_{omax}$ : Maximum outdoor temperature;  $T_{omin}$ : Minimum outdoor temperature;  $T_{iav}$ : Average indoor temperature;  $T_{imax}$ : Maximum indoor temperature;  $T_{imin}$ : Minimum indoor temperature; CL: Cooling; FR: Free running; HT: Heating; SM: summer; WT: winter; SP: Spring; AU: Autumn; C: Cold region; T: Temperate region; ST: Sub-tropical region;  $T_{mrt}$ : Indoor mean radiant temperature;  $T_{op}$ : Operative temperature;  $T_{in}$ : Indoor temperature;  $T_g$ : Globe temperature;  $T_c$ : Comfort temperature, CB: Combined; MS: Monsoon; LA: Low altitude; MA: Mid altitude; HA: High altitude.

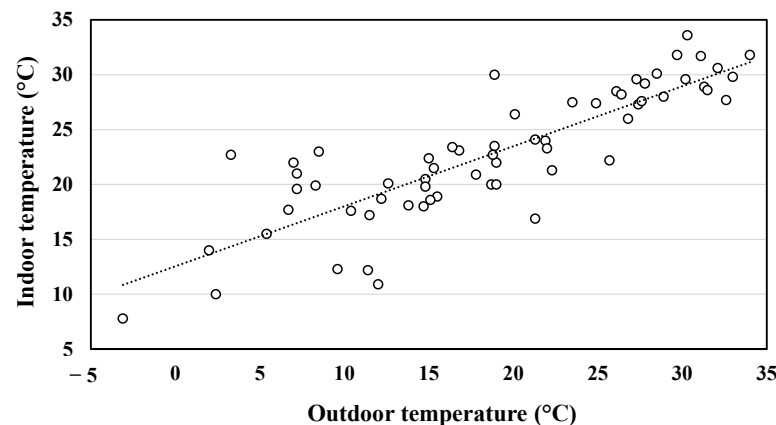


Figure 5. Correlation between indoor and outdoor temperatures.

$T_i$  is indoor air temperature ( $T_g$ ,  $T_{in}$ ,  $T_{op}$ ) while  $T_o$  is outdoor air temperature ( $T_{rm}$ ,  $T_m$ ,  $T_{out}$ ) from all published papers included in this study.  $n$  is the number of samples and  $R^2$  is the coefficient of determination,  $S.E.$  is the standard error of regression coefficient and  $p$  is the significant value of regression coefficient. A better understanding of residential thermal conditions is necessary as there are potential changes in ambient temperature due to different climatic condition.

### 3.4. Relationship between Thermal Sensation Vote (TSV) and Indoor Temperature

Thermal sensation vote (TSV) is an important element in the field of thermal comfort. It provides a measurement on how people were feeling in a certain environment. It has been mentioned that the TSV for each person is more sensitive to indoor temperature in winter rather than in summer [54]. Thus, we collected regression equations for TSV and indoor air temperature from several previous studies as shown in Table 2 to be compared in terms of season (condition), operation modes and types of building. The temperature required to change one unit scale of TSV ( $T_{req}$ ) was also provided at which can be obtained from the regression coefficient of the equation. Various value for the  $T_{req}$  from different previous studies can be seen in Table 2. For instance, the regression coefficient of 0.395 in a study from Djamila et al. [58] obtained 2.5 °C ( $=1/0.395$ ) to shift one unit scale of TSV. A previous study reported that a higher degree of thermal adaptability of occupants in residential buildings compared to occupants in office buildings has been found at which the temperature change to shift one unit on the 7-point thermal sensation scale is 6.3 K [75].

Table 2. Regression equations of TSV and indoor air temperature from previous studies.

Reference	Types of Building	Operation Modes	Condition	Regression Equation	$R^2$	$S.E.$	$T_{req}$ (°C)	Range of $T_{in}$ (°C)	Range of TSV
Yu et al. [6]	Traditional, solar houses	Mixed	WT	$TSV = 0.121T_{op} - 1.8$	0.92	-	8.3	1–25	−3 to +3
		FR	SM	$TSV = 0.192T_{op} - 4.2$	0.87	-	5.2	13–29	
Rijal et al. [7]	Condominium	CL	-	$TSV = 0.066T_{op} + 2.5$	0.12	0.002	15.2	14–31	1 to 7
		HT	-	$TSV = 0.002T_{op} + 3.8$	0.0001	0.004	500	13–28	
Xu et al. [53]	Traditional houses	FR	SM	$TSV = 0.235T_{op} - 6.6$	0.19	-	4.3	25–34	−3 to +3
		FR	WT	$TSV = 0.095T_{op} - 1.5$	0.13	-	10.5	2–18	
Thapa et al. [70]	Wood houses with low height	FR	LA	$TSV = 0.130T_g - 2.9$	0.23	-	7.7	14–25	−3 to +3
		FR	HA	$TSV = 0.138T_g - 2.5$	0.13	-	7.2	9–22	
		FR	CB	$TSV = 0.088T_g - 1.8$	0.09	-	11.4	9–25	
		HT	WTB	$TSV = 0.107T_{op} - 2.2$	0.84	0.014	9.3	−15–5	
Yan et al. [57]	Modern houses	CL	SMB	$TSV = 0.241T_{op} - 6.5$	0.89	0.024	4.1	22–39	−3 to +3
		HT	WTS	$TSV = 0.148T_{op} - 2.7$	0.86	0.016	6.8	1–12	
		FR	SMS	$TSV = 0.355T_{op} - 9.8$	0.96	0.019	2.8	27–38	
Wei et al. [54]	High-rise & multi-story building	FR	SP	$TSV = 0.043T_{op} - 0.8$	0.36	-	23.3	18–27	−3 to +3
		FR	SM	$TSV = 0.314T_{op} - 8.2$	0.86	-	3.2	26–34	
		FR	AU	$TSV = 0.050T_{op} - 1.3$	0.59	-	20.0	13–27	
		FR	WT	$TSV = 0.163T_{op} - 2.8$	0.63	-	6.1	16–25	

Table 2. Cont.

Reference	Types of Building	Operation Modes	Condition	Regression Equation	$R^2$	S.E.	$T_{req}$ (°C)	Range of $T_{in}$ (°C)	Range of TSV
Yang et al. [56]	Residence in high latitude	Mixed	WT	$TSV = 0.141T_{in} - 2.7$	0.64	-	7.1	2–20	−3 to +3
		FR	SM	$TSV = 0.183T_{in} - 4.2$	0.75	-	5.5	17–27	−3 to +3
Djamila et al. [58]	-	FR	HH	$TSV = 0.395T_{in} - 11.9$	0.17	-	2.5	27–35	−3 to +3
Cao et al. [76]	Apartments	HT	IH	$TSV = 0.172T_{in} - 3.2$	0.81	-	5.8	16–23	−3 to +3
		DH		$TSV = 0.211T_{in} - 4.6$	0.88	-	4.7	16–23	−3 to +3
		FR		$TSV = 0.120T_{in} + 1.2$	0.47	0.001	8.3	5–36	
Rijal et al. [66]	-	CL	-	$TSV = 0.098T_{in} + 1.5$	0.08	0.004	10.2	18–36	1 to 7
		HT		$TSV = 0.081T_{in} + 2.0$	0.09	0.004	12.3	7–28	
Malik and Bardhan [69]	Low-cost building	FR	-	$TSV = 0.260T_{in} - 7.5$	0.32	-	3.8	25–34	−3 to +3
Costa-Carrapico et al. [77]	Vernacular dwellings	Mixed	WT	$TSV = 0.461T_{in} - 7.5$	0.88	0.394	2.2	10–17	−3 to +3
		Mixed	SM	$TSV = 0.522T_{in} - 14.1$	0.81	0.326	1.9	27–31	−3 to +3

TSV: Thermal sensation vote; CL: Cooling; FR: Free running; HT: Heating; SM: summer; WT: winter; SP: Spring; AU: Autumn; HH: Hot and humid region; IH: Individual heating; DH: Direct heating;  $T_{in}$ : Indoor temperature; WTB: Winter in Beijing; SMB: Summer in Beijing; WTS: Winter in Shanghai; SMS: Summer in Shanghai;  $T_{op}$ : Operative temperature;  $T_g$ : Globe temperature;  $T_{req}$ : Required indoor temperature to change one scale unit of TSV; CB: Combined; LA: Low altitude; HA: High altitude.

In order to see the relationship between TSV and indoor temperatures, we illustrated the regression equations from Table 2 in the form of lines, as shown in Figure 6 [6,7,53,54,56–58,66,69,70,76,77]. TSV could rate the people's perception by using a scale from −3 to +3 or 1 to 7. Both scales share the same meaning and thus they were indicated in the same y-axis. The regression coefficient varied from 0.04 to 0.52. This can be supported by Nicol and Humphreys [78], who mentioned that within different climate of indoor air temperature, the mean comfort vote changed even less than what was presumed. Some of the equations have low slope which indicates the low thermal sensitivity of the resident for a given indoor temperature. This proved that the estimation of comfort temperature might not be reliable when the value of regression coefficient is lower than 0.25 [49]. Therefore, the use of Griffiths' method is more useful when the slope from the regression method is not reliable.

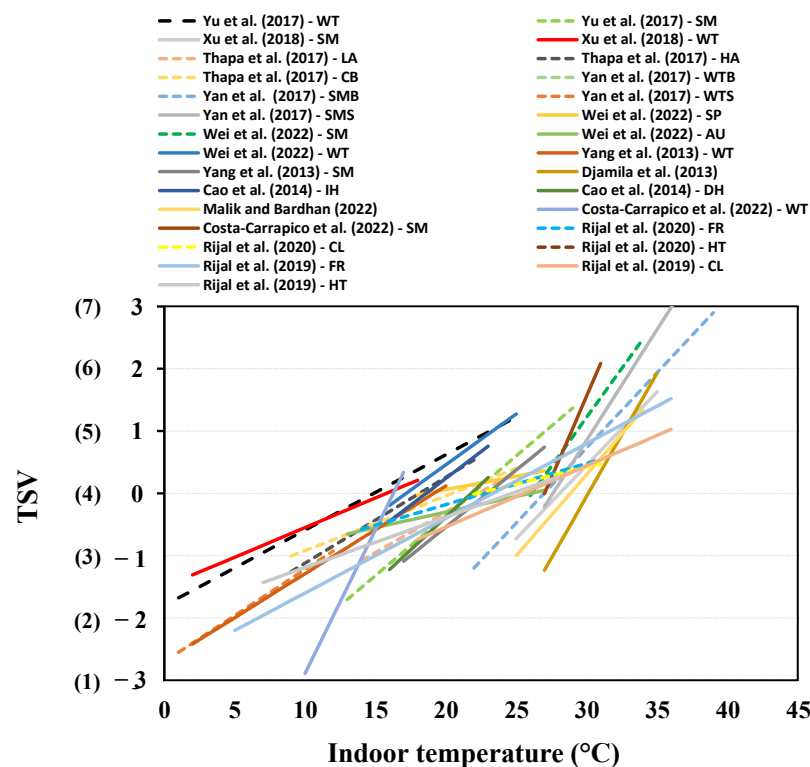


Figure 6. Regression line for TSV and indoor air temperature [6,7,19,20,22–24,33,39,40,47,74,75].

### 3.5. Variation of Comfort Temperatures

Most behavior adaptations, such as adjusting clothing, opening windows, or consuming cold or hot drinks are being applied to the case of residential buildings. This is due to the full control of the residents on their preferred thermal conditions. A comparison between users with district heating and individual heating in 10 houses in China revealed that the variation of clothing insulation was clearer for the users of individual heating, and they were more willing to adjust their clothing, and thus their comfort temperature was lower than the users of district heating by 3.4 °C [76]. Other than that, the thought of the resident to pay a higher bill for a higher energy consumption will widen the acceptable comfort temperature range.

This can be confirmed by conducting a field measurement and survey where the occupants fill out questionnaires about their thermal sensations and thermal preferences. This procedure was carried out concurrently with measurement of the indoor air temperature, relative humidity or air velocity. The variation of comfort temperature in Table 1 ranges from 10.7–30.2 °C. An acceptable range from 22.0–25.9 °C in houses with hot and humid condition was identified from one field measurement study in China [4]. A study from Gong et al. [5] determined the thermal comfort range, which was observed at operative temperatures of 20.9–27.5 °C in summer and 12.2–20.1 °C in winter. During heating season in Beijing, China, the comfort temperature of 22.5 °C has been recorded [52]. While in Nanjing, China, the comfort temperature was 15.8 °C [53]. As the field of thermal comfort studies in residential buildings shows a diverse environment where residents feel comfortable, it is feasible to generalize the findings that specifically focus on residential building with different climatic conditions, seasons, types of residential buildings and operation modes.

### 3.6. Comfort Threads in Different Building Operation Modes

#### 3.6.1. Relationship between Comfort Temperature and Indoor Temperatures

Within different houses or dwellings, comfort temperature is supposed to be varied and different. Song et al. [20] mentioned that occupants in a different thermal environment with a different air temperature and radiant temperature could have an impact on the levels of human thermal comfort. Figure 7 shows the correlation of mean comfort temperature with average indoor. All related data can be referred to Table 1. Each operation mode, such as FR, HT, and mixed are indicated by a different point, which also represents the comfort temperature for each measured indoor temperature. The value for the coefficient of determination was 0.78 for all data. It shows that people will indeed adjust to their thermal surroundings and feel at ease or comfortable in various indoor conditions. This can be proved by almost 70% of the comfort temperatures data, which have 0–2 °C differences from the indoor temperature. The regression equations are given below:

$$\text{FR: } T_c = 0.722T_i + 6.0 \quad (n = 24, R^2 = 0.65, S.E. = 0.08, p < 0.001) \quad (4)$$

$$\text{HT: } T_c = 0.799T_i + 4.2 \quad (n = 6, R^2 = 0.97, S.E. = 0.08, p < 0.001) \quad (5)$$

$$\text{Mixed: } T_c = 0.627T_i + 8.9 \quad (n = 31, R^2 = 0.81, S.E. = 0.06, p < 0.001) \quad (6)$$

$$\text{All: } T_c = 0.662T_i + 7.7 \quad (n = 68, R^2 = 0.78, S.E. = 0.04, p < 0.001) \quad (7)$$

Regression equation for CL mode was not statistically significant. Several studies confirmed that the comfort temperature is related to the indoor temperature, and thus Table 3 lists regression equations from several previous studies. The equation for comfort and indoor temperatures in FR mode for this study is quite similar with other studies, such as in Thapa and Indraganti [68] and Rijal et al. [66].

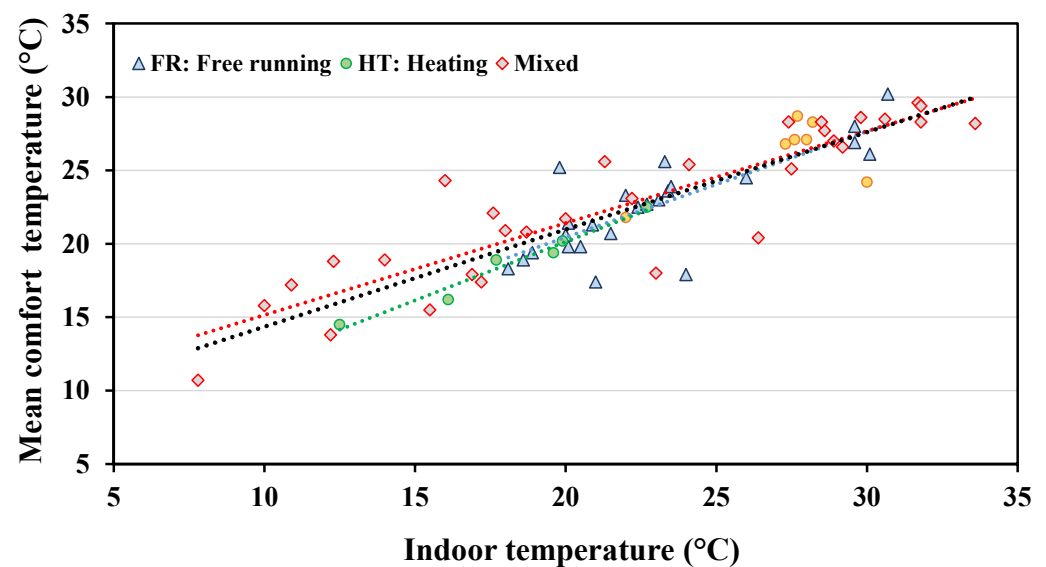


Figure 7. Correlation of mean comfort temperature with indoor temperature.

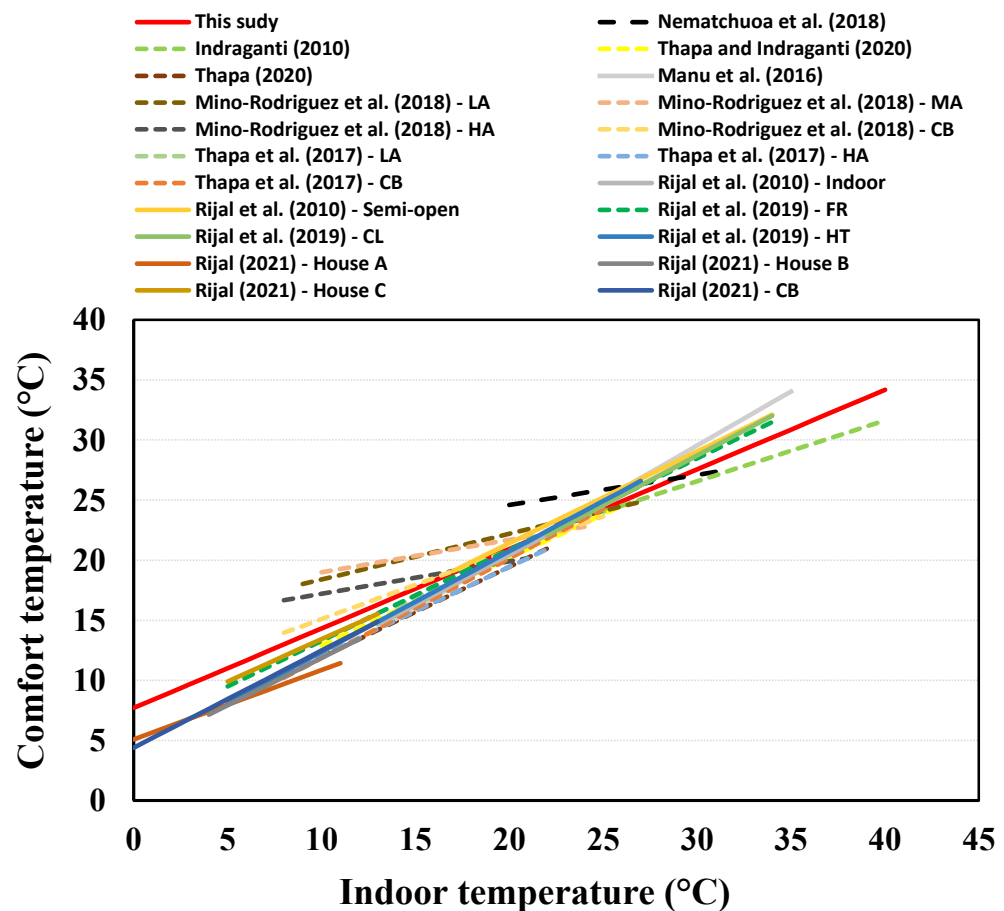
Table 3. Regression equations from previous studies.

Reference	Types of Building	Operation Modes	Condition	Regression Equation	$R^2$	S.E.	Range of $T_i$ (°C)
This study	All	FR	-	$T_c = 0.722T_i + 6.0$	0.65	0.08	0~40
		HT		$T_c = 0.799T_i + 4.2$	0.97	0.08	
		Mixed		$T_c = 0.627T_i + 8.9$	0.81	0.06	
		All		$T_c = 0.662T_i + 7.7$	0.78	0.04	
Nematchuoa et al. [73]	Traditional residence	FR	Dry & rainy	$T_c = 0.250T_{in} + 19.6$	0.78	-	24~34
Indraganti [79]	Apartments	FR	Peak summer & monsoon	$T_c = 0.506T_g + 11.4$	0.23	-	27~42
Thapa [15]	Single-story houses	FR	Cold & warm	$T_c = 0.752T_{op} + 4.4$	0.72	-	9~22
Thapa and Indraganti [68]	NV Residential	FR	Cold & warm	$T_c = 0.727T_{op} + 5.6$	0.66	-	9~27
Manu et al. [80]	Offices and residential	Mixed	Cold & warm	$T_c = 0.90T_{op} + 2.5$	0.97	-	13~40
Mino-Rodriguez et al. [60]	-	FR	LA	$T_c = 0.380T_{op} + 14.6$	0.38	-	9~27
			MA	$T_c = 0.270T_{op} + 16.3$	0.28	-	10~24
			HA	$T_c = 0.270T_{op} + 14.5$	0.30	-	8~21
			CB	$T_c = 0.570T_{op} + 9.4$	0.58	-	8~27
Thapa et al. [70]	Wood houses with low height	FR	LA	$T_c = 0.739T_{op} + 5.8$	0.71	-	14~25
		FR	HA	$T_c = 0.737T_{op} + 4.7$	0.51	-	8~22
		FR	CB	$T_c = 0.827T_{op} + 3.6$	0.83	-	8~25
		Mixed	Indoor	$T_c = 0.827T_g + 3.9$	0.99	-	13~32
Rijal et al. [63]	Traditional houses	Mixed	Semi-open	$T_c = 0.765T_g + 6.1$	0.99	-	17~34
Rijal et al. [66]	-	FR	-	$T_c = 0.759T_{in} + 5.7$	0.90	0.002	5~34
		CL		$T_c = 0.804T_{in} + 5.0$	0.58	0.008	22~34
		HT		$T_c = 0.837T_{in} + 4.0$	0.73	0.009	5~27
		Mixed		$T_c = 0.576T_g + 5.1$	0.52	0.024	0~11
Rijal [49]	Traditional houses	Mixed	House A	$T_c = 0.786T_g + 4.0$	0.31	0.054	4~12
		Mixed	House B	$T_c = 0.703T_g + 6.4$	0.36	0.040	5~13
		Mixed	House C	$T_c = 0.703T_g + 6.4$	0.36	0.040	5~13
		Mixed	CB	$T_c = 0.808T_g + 4.4$	0.55	0.018	0~13

CL: Cooling; FR: Free running; HT: Heating; SM: summer;  $T_{op}$ : Operative temperature;  $T_{in}$ : Indoor temperature;  $T_g$ : Globe temperature;  $T_c$ : Comfort temperature;  $T_i$ : Indoor temperature ( $T_{op}$ ,  $T_g$  or  $T_{in}$ ); CB: Combined; LA: Low altitude; MA: Mid altitude; HA: High altitude.

Then, these equations are illustrated in Figure 8 as ‘comfort threads’. A shallower slope for the regression line of Nematchuoa et al. [73] and Mino-Rodriguez et al. [60] can be seen compared to the other studies, where the slope ranged from 0.5 to 0.9. There might be a connection between the variations in building design and thermal responses for each building type.





**Figure 8.** Regression line for comfort temperature with indoor temperature ranges [26,30,31,33,37–39,43,76,77].

### 3.6.2. Relationship between Comfort Temperature and Outdoor Temperature

Humphreys [47], de Dear and Brager [48], and Humphreys and Nicol [81] found that comfort temperature correlates with outdoor air temperature. This makes it possible to estimate how the outdoor temperature will affect the temperature of an indoor space. Figure 9 shows the correlation of mean comfort temperature with average outdoor temperature. All related data can be referred to Table 1. Each operation mode, such as FR, CL, and mixed, is indicated by a different point, which also represents the comfort temperature for each measured outdoor temperature. The value for the coefficient of determination was 0.73 for all data. This shows that people are largely adjusting to their thermal surrounding and found comfort condition in a range of outdoor temperature. However, only 25% of the comfort temperatures data has a 0–2 °C difference from the outdoor temperature. This might be due to the higher comfort temperature during the winter season in heating mode. When outdoor temperature ranges from 2–12 °C, the residents feel comfortable at a temperature of 14–22 °C. The regression equations are given below:

$$\text{FR: } T_c = 0.398T_o + 14.9 \quad (n = 22, R^2 = 0.54, S.E. = 0.08, p < 0.001) \quad (8)$$

$$\text{CL: } T_c = 0.273T_o + 19.7 \quad (n = 7, R^2 = 0.92, S.E. = 0.04, p = 0.001) \quad (9)$$

$$\text{Mixed: } T_c = 0.459T_o + 13.7 \quad (n = 30, R^2 = 0.83, S.E. = 0.04, p < 0.001) \quad (10)$$

$$\text{All: } T_c = 0.409T_o + 15.1 \quad (n = 63, R^2 = 0.73, S.E. = 0.03, p < 0.001) \quad (11)$$

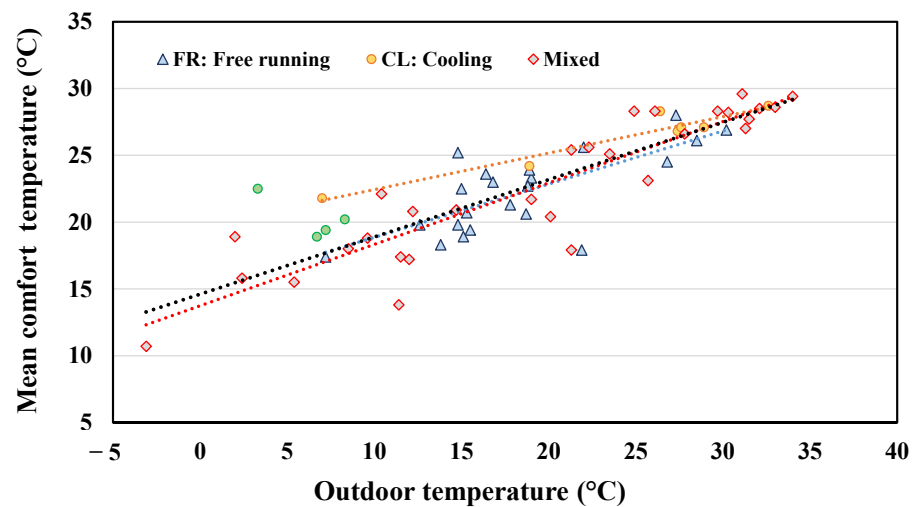


Figure 9. Correlation of mean comfort temperature with outdoor temperature.

Regression equation for HT mode was not statistically significant. As shown in Table 4, there is a significant correlation between the comfort temperature and outdoor temperature from the majority of field measurement studies in the field of adaptive thermal comfort. The equation for comfort and outdoor temperature in FR mode for this study is quite similar with other studies, such as in Rijal et al. [7], Wei et al. [54] and ASHRAE standard. Then, all adaptive comfort equations from Table 4 are illustrated as ‘comfort threads’ in Figure 10 for better understanding. For FR and mixed mode, the slopes are steeper than in CL mode. It suggests that the residents were adapting to diverse outdoor conditions more in FR and mixed mode rather than in CL mode. A previous study also mentioned a similar result at which they obtained a lower slope (0.15) in CL mode and a higher slope (0.26) in FR mode [82].

Table 4. Adaptive thermal comfort equation from previous studies.

Reference	Types of Building	Operation Modes	Condition	Adaptive Equation	$R^2$	S.E.	Range of $T_o$ (°C)
This study	All	FR	-	$T_c = 0.398T_o + 14.9$	0.54	0.080	−1~36
		CL		$T_c = 0.273T_o + 19.7$	0.92	0.040	
		Mixed		$T_c = 0.459T_o + 13.7$	0.83	0.040	
		All		$T_c = 0.409T_o + 15.1$	0.73	0.030	
Rijal et al. [7]	Condominium	FR	-	$T_c = 0.370T_{rm} + 16.8$	0.67	0.003	−2~34
		CL	-	$T_c = 0.160T_{rm} + 22.5$	0.05	0.027	9~36
		HT	-	$T_c = 0.310T_{rm} + 17.7$	0.14	0.012	−2~24
Humphreys and Nicol [81]	-	FR	-	$T_c = 0.534T_{out} + 11.9$	-	-	0~34
Kim et al. [83]	Homes with AC	CL	Cold & warm	$T_c = 0.26T_{out} + 16.75$	0.37	-	15~35
Costa-Carrapico et al. [77]	Vernacular dwelling	CL	SM	$T_c = 0.30T_m + 17.9$	-	-	22~36
		FR	WT	$T_c = 0.43T_m + 15.6$	-	-	6~11
Udaykumar et al. [84]	Apartments	CL	SM	$T_c = 0.89T_{out} + 4.86$	0.97	-	16~35
Safarova et al. [85]	Residential	CL	SM	$T_c = 0.31T_m + 17.6$	-	-	15~35
Thapa [15]	Single-story residential houses	FR	Cold & warm	$T_c = 0.605T_{rm} + 18.4$	0.74	-	6~18
Thapa et al. [70]	Houses with low height & made up of wood	FR	LA	$T_c = 0.587T_{out} + 9.8$	0.66	-	8~26
			HA	$T_c = 0.466T_{out} + 11.7$	0.33	-	1~21
			CB	$T_c = 0.527T_{out} + 10.9$	0.64	-	1~26

Table 4. Cont.

Reference	Types of Building	Operation Modes	Condition	Adaptive Equation	$R^2$	S.E.	Range of $T_o$ (°C)
Indraganti [79]	Apartments	FR	SM & MS	$T_c = 0.260T_{out} + 21.4$	-	-	26~35
Yang et al. [56]	-	Mixed	HA	$T_c = 0.474T_{out} + 13.8$	-	-	-1~5
Wei et al. [54]	High-rise & multi-story building	FR	SM	$T_c = 0.16T_{out} + 22.9$	-	-	22~33
		FR	AU	$T_c = 0.42T_{out} + 15.0$	-	-	13~26
		FR	WT	$T_c = 0.15T_{out} + 18.9$	-	-	1~15
		FR	-	$T_c = 0.480T_{out} + 14.4$	0.70	0.002	-1~35
Rijal et al. [66]	-	CL	-	$T_c = 0.180T_{out} + 22.1$	0.02	0.014	15~35
		HT	-	$T_c = 0.193T_{out} + 18.3$	0.05	0.014	-1~25

CL: Cooling; FR: Free running; HT: Heating; SM: summer; WT: winter; AU: Autumn;  $T_{rm}$ : Running mean outdoor temperature;  $T_m$ : Monthly mean outdoor temperature;  $T_{out}$ : Outdoor temperature;  $T_o$ : Outdoor temperature ( $T_{rm}$ ,  $T_m$  or  $T_{out}$ );  $T_c$ : Comfort temperature, LA: Low altitude; MA: Mid altitude; HA: High altitude; MS: Monsoon.

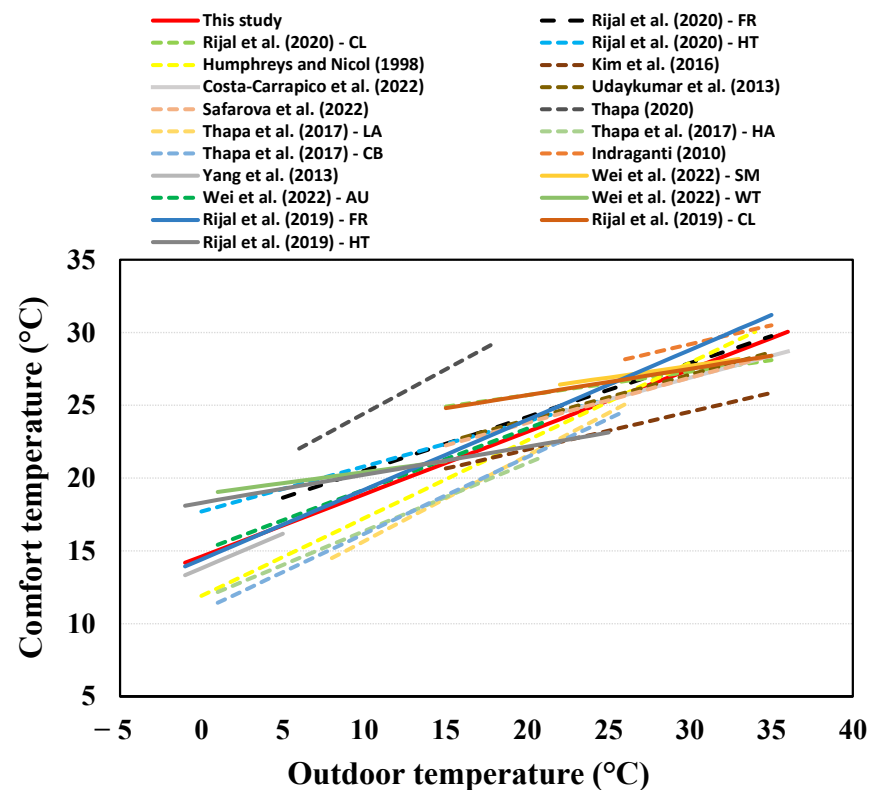


Figure 10. Regression line for comfort temperature with outdoor temperature ranges [7,20,23,33,37,39,75,76,79–82].

### 3.7. Energy Saving Potential Based on Thermal Comfort

The outcomes from the thermal comfort studies always provided several options for the residents to implement energy-saving while identifying their comfort temperature. The measurement and survey results were then compared to the recommended comfort range, and recommendations for the potential of energy saving were proposed. However, obtaining a balance between thermal comfort and energy efficiency in buildings remained a challenge for the building engineers. When attempting to save energy consumption, human comfort is frequently overlooked [24]. Therefore, studies which cover the issue of indoor thermal comfort have grown in popularity because of the need to reduce energy consumption in residential buildings. Most of the case studies emphasized either simply setting a higher summer set point temperature (SST) or implementing a wider range of indoor design temperatures for different times of the day and different outdoor condi-

tions [34]. Other than that, cooling energy can be saved up to 6–7% by applying the depth of the window shading device of 60 cm [86].

Indoor temperature can be changed by opening the window and thus reducing environmental impact as the consumption of air conditioning is reduced [87]. Therefore, Table 5 lists several energy implications from previous studies that utilized the use of natural ventilation and adaptive measures. A previous study obtained 13.2% of energy saving by increasing the thermostat set point 6 °C to maintain the occupant's comfort at 24.4–27.2 °C [43]. Other than that, employing load shedding would automatically shed load which directly modified the air handling unit fan speed. This could be resulted in a poor air distribution and occupant discomfort [88]. Thus, it is critical to investigate the applicability of thermal comfort standards and the use of building adaptation to determine the impact on residential energy consumption.

**Table 5.** Energy saving potential by adaptive measures from previous studies.

Reference	Types of Building	Operation Modes	Condition
United States	Sadineni and Boehm [89]	Raise SST from 23.9 °C to 26.1 °C (during 16:00–19:00).	Peak electrical energy demand reduced by 69%.
Saudi Arabia	Al-Sanea and Zedan [90]	Change yearly-fixed Thermostat setting (21–24.1 °C) to optimized monthly fixed settings (20.1–26.2 °C).	Energy cost reduced by 27–34%.
Spain	González-Lezcano and Hormigos-Jimenez [91]	Natural ventilation	13% cooling energy saving by natural ventilation
Spain	Barbadilla-Martín et al. [92]	Implementation of the algorithm in the HVAC control system, both during the cooling and the heating period	Obtaining savings of 28% and 11%, respectively
Romania	Dan et al. [93]	Using polystyrene thermal insulation with a thickness of 300 mm (walls), 425 mm (roof), heat recovery, proper orientation and air-tight envelope	Satisfy the criteria of passive house design which aims for less than 120 kWh/year (total energy use) and below than 15 kWh/year (cooling/heating demand)
Qatar	Al Hoor et al. [94]	Optimize the operational mode of cooling system from wet to dry mode; the variation in cooling performance (41% at most)	Save 43% of cooling demand compared to dry mode.
Iran	Heidari et al. [95]	Utilization of different shading devices; overhang, side fins, overhang and side fins, eggcrate, vertical, horizontal, geometrical	Horizontal, geometrical and eggcrate have the best function according to reduce energy and have enough day lighting
Jordan	Jaber and Ajib [96]	Passive façade facing south orientation, optimum size of windows and shading device, and optimum insulation thickness (0.2 m for roof and 0.13 m for ceiling)	Energy saving potential of 28% from yearly energy use
Spain	Sánchez et al. [97]	Changed the conventional fixed threshold to the adaptive energy demand	80% of cooling energy reduced while 20% for heating load

#### 4. Overall Discussion

The large variation of comfort temperature mostly depends on the climatic condition and operation modes. The climate involved in this study can be classified as temperate, tropical, sub-tropical, continental and polar. There is a clear difference between the comfort temperature of the residents in polar (10.7 °C) and tropical (30.2 °C) climate within the operation mode of FR and mixed. This proved that the residents would adopt to a different level of adaptation in a different climate. The differences also depend on the seasons and operation modes.

The relationship of comfort temperature with indoor and outdoor temperatures are clearly illustrated as the ‘comfort threads’ in this study. It shows that the correlations are quite high and explains that people are adapting to a large variation of indoor and outdoor temperatures. Moreover, regression method may not be appropriate for estimating comfort temperature as it has flaws, for example, when the temperature range is narrow or the number of respondents is small, the comfort temperature might fall far from the real response. Some potential energy saving for residential buildings can be proved by implementing adaptation measures. The adaptation measures can be in terms of human adaptation by changing the temperature setting of air conditioners, using natural ventilation, or building adaptation, such as implementing well designed buildings for the purpose of energy saving, such as roof retrofitting [98], building orientation [99], shading design [95] and others.

The limitation of this study is that only the Scopus database was utilized as the base searching method, which only searches terms in the title, abstract and keywords rather than in the main text. A more systematic publication collection approach could be derived in the future. However, the Scopus database covers a wide range of papers, and thus the conclusions of this paper would be similar even though we included the other database for this study.

## 5. Conclusions

This review paper identifies the trends for present thermal comfort studies in residential buildings and several important points that could have an impact on energy saving potential. The following points can be concluded from this review.

1. Adaptive comfort models for residential buildings tend to have a wider range of comfort temperature for different countries, climates, and operation modes. Comfort temperature varies at the range of 10.7 to 30.2 °C. Specifically, in the condition of FR, CL, HT and mixed, the mean comfort temperatures are 26.1 °C, 22.5 °C, 18.6 °C and 22.7 °C, respectively. In a temperate climate, the mean comfort temperature is 22.9 °C, while it is 24.5 °C, 23.4 °C, 21.7 °C and 10.7 °C for tropical, sub-tropical, continental and polar climate, respectively.
2. The comfort temperature can be estimated from indoor or outdoor temperature. Thus, ‘comfort threads’ can be used as a visualization to show the observation of how comfort temperature is diverse in residential buildings according to different indoor and outdoor air temperatures. It provided observation of the slope’s differences, which can be related to building design and thermal responses. ‘Comfort threads’ also suggest that the occupants in a residential building could adapt to diverse outdoor conditions more in FR and mixed mode rather than in CL.
3. A significant energy savings for residential buildings can be found in both CL and FR modes. In summer, if people are willing to bear a greater indoor temperature, the cooling system will be rarely used. Aside from the potential for energy saving, raising the summer set point temperature could significantly reduce the peak demand for electricity consumption. Previously published papers usually provided an adaptive thermal comfort equation for their own studies, however most of the authors tended to mix the data from FR, CL, and HT operation modes to propose one overall adaptive comfort model. Thus, adaptive thermal comfort equation of free running mode for residential buildings were proposed as follows:

$$T_c = 0.398T_o + 14.9$$

In comparison with the ASHRAE adaptive model, the regression coefficient was slightly higher in this study.

The results obtained from this review indicate that there is a pressing need for the development of adaptive thermal comfort models that will improve not only the comfort requirements but also building energy performance.



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## Abbreviations

SDGs	Sustainable Development Goals
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
CO <sub>2</sub>	Carbon dioxide
TSV	Thermal sensation vote
CL	Cooling
FR	Free running
HT	Heating
SM	Summer
WT	Winter
SP	Spring
AU	Autumn
C	Cold region
T	Temperate region
ST	Sub-temperate region
CB	Combined
MS	Monsoon
LA	Low altitude
HA	High altitude
MA	Mid altitude
HH	Hot and humid region
IH	Individual heating
DH	Direct heating
$T_{oav}$	Average outdoor temperature (°C)
$T_{omax}$	Maximum outdoor temperature (°C)
$T_{omin}$	Minimum outdoor temperature (°C)
$T_{iav}$	Average indoor temperature (°C)
$T_{imax}$	Maximum indoor temperature (°C)
$T_{imin}$	Minimum indoor temperature (°C)
$T_{mrt}$	Indoor mean radiant temperature (°C)
$T_{op}$	Operative temperature (°C)
$T_{in}$	Indoor temperature (°C)
$T_g$	Globe temperature (°C)
$T_c$	Comfort temperature (°C)
$T_{req}$	Required indoor temperature to change one scale unit of TSV (°C)
$T_i$	Indoor temperature ( $T_{op}$ , $T_g$ and $T_{in}$ ) (°C)
$T_{rm}$	Running mean outdoor temperature (°C)
$T_m$	Monthly mean outdoor temperature (°C)
$T_{out}$	Outdoor temperature (°C)
$T_o$	Outdoor temperature ( $T_{rm}$ , $T_m$ and $T_{out}$ ) (°C)

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