

Article

Towards Sustainable Living through Thermoneutral Temperature Management in Subtropical Steppe Climates

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Abstract: This study addresses the critical interplay between sustainable living and thermal comfort within residential buildings in subtropical steppe (BSh) climates, particularly in Northern Iraq. With the global imperative to enhance energy efficiency and occupant well-being, this research emphasizes the identification of thermoneutral indoor air temperature ranges that both support sustainable energy use and ensure the occupants' thermal comfort. By analyzing the acceptable temperature limits across different building orientations during summer and winter, the study utilizes the predicted mean vote–predicted percentage dissatisfied (PMV-PPD) index approach to establish thermal comfort thresholds. The findings reveal that the optimal summer and winter indoor air temperatures are 29.2 °C and 19.4 °C, respectively, with variations across orientations highlighting the significant influence of building directionality on achieving thermoneutral conditions. A wider range of accepted temperatures exists in the eastward orientation in summer (between 26.6 °C and 29.2 °C). The study advances our understanding of sustainable thermal comfort practices, proposing orientation-specific temperature ranges as a cornerstone for reducing energy consumption without compromising occupant comfort in subtropical steppe climates.

Keywords: thermal comfort; thermal predicted vote; thermoneutral temperature; inner air temperature; subtropical steppe climate



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1. Introduction

In the quest for sustainable living, thermal comfort emerges as an essential element, accounting for a substantial portion of energy consumption in buildings post-occupancy [1]. The efficient evaluation of thermal comfort is instrumental in the environmental design of building interiors, ensuring occupants' comfort while significantly reducing energy consumption [2]. The growing urgency to address climate change and environmental degradation accentuates the need for sustainable building designs that minimize energy use [3].

Garmian, located in the Kurdistan region of Iraq, exhibits distinct climatic conditions classified under the Köppen–Geiger system as subtropical steppe—BSh [4]. These conditions are marked by extreme temperatures—plunging below zero in winter and soaring up to 50 °C in summer [5]. In this region, a significant portion of energy consumption in buildings is attributed to maintaining thermal comfort [6,7], further complicated by persistent electricity supply disruptions since 1990 [8]. These factors highlight the critical need for sustainable strategies to achieve thermal comfort in buildings.

Air temperature is recognized as a primary determinant influencing thermal comfort [9]. Establishing a range of air temperatures conducive to thermal comfort is essential for creating satisfactory indoor environments and has a profound impact on energy consumption. By maintaining indoor air temperatures within a neutral thermal range,

designers can significantly reduce energy use by efficiently sizing and selecting Heating, Ventilation, and Air Conditioning (HVAC) systems that maintain thermal neutrality without excessive energy consumption [10]. Ref. [11] demonstrates that a slightly wider temperature band within comfort limits can lead to substantial energy savings. Given the diverse temperature spectrums across different climatic regions [12], understanding these variations is crucial for designers to tailor their approaches to specific regional conditions.

Comparative studies reveal the broad spectrum of indoor thermal comfort temperatures across various climates. For instance, the indoor thermal comfort temperature in subtropical Japanese dwellings ranges from 17.0 to 30.0 °C [13], while, in Malaysia, Indonesia, and Singapore, the comfort temperatures in air-conditioned buildings are reported as 25.6 °C, 26.3 °C, and 26.4 °C, respectively [14]. In the hot and arid climate of Shiraz, Iran, comfort temperatures range from 22.0 to 25.0 °C [15], and in the diverse climates of India, the range is from 22.5 to 30.6 °C [16]. Australian buildings exhibit a thermal comfort range from 19.5 to 26.6 °C [17], contrasting with the 20.2–20.9 °C range observed in Coventry, UK [18]. ASHRAE-55 standards suggest an acceptable indoor air temperature range of 23–26 °C [9].

The design of HVAC systems requires a profound understanding of thermal comfort temperature thresholds. An in-depth knowledge of acceptable indoor temperature boundaries enables the efficient design and selection of HVAC systems to maintain thermal neutrality efficiently, minimizing unnecessary energy use. Current thermal comfort research, aligning with (International Organization for Standardization) ISO 7730 [19] and (American Society of Heating, Refrigerating and Air-Conditioning Engineers) ASHRAE 55 standards [9], suggests that indoor thermal conditions often fall within a neutral range of 22.2 °C to 26 °C, with occupants reporting a preference for slight coolness, contributing to higher comfort and acceptability levels [20].

This study seeks to establish thermal comfort scenarios in residential buildings within the subtropical steppe (BSh) climate of Garmian, in the northeastern region of Iraq. It aims to identify the thermoneutral temperature ranges suitable for summer and winter, considering building orientations. The research further investigates the PMV-PPD index by examining environmental and personal factors, enhancing our understanding of sustainable thermal comfort. This approach not only contributes to energy efficiency but also aligns with global sustainability goals, addressing the pressing need for climate-adaptive building design in regions experiencing extreme climatic conditions.

2. Materials and Methods

2.1. Air Temperature's Role in Thermal Comfort

Fanger elucidates the concept of thermal comfort from a physiological perspective, contending that an individual's perception of comfort is contingent upon the physiological strain imposed by the surroundings [21] (p. 124). The widely accepted international articulation of thermal comfort resides in ASHRAE Standard 55, which defines it as the condition of mental contentment with the thermal environment, gauged through personal assessment [22]. The analysis of thermal comfort can be conducted in two ways: objective and subjective [23]. This study will be limited to evaluating thermal comfort in an objective way only.

Objective aspects encompass air temperature, air velocity, relative humidity, mean radiant temperature (radiation), occupants' activity levels, and clothing choices [24–26]. Conversely, subjective considerations encompass non-quantifiable elements such as psychological and contextual aspects like prior experiences, thermal expectations, duration of exposure to ambient conditions, opportunities for acclimatization, and socio-cultural influences [23,24,27].

One of these measurable parameters is air temperature (T_a), which serves as an evaluative metric for the thermal environment. The role of air temperature in the assessment of thermal comfort cannot be overstated. The ASHRAE Standard 55, a widely recognized guideline for thermal comfort, identifies air temperature as a primary factor affecting the

human perception of comfort [9]. The temperature of the indoor environment directly influences human physiological responses, including metabolic rate, skin temperature, and thermal sensations. Research by de Dear and Brager [28] underscores the critical importance of air temperature in thermal comfort models. They highlight that deviations from the optimal temperature range can lead to discomfort, resulting in increased energy consumption as occupants seek to modify the environment through heating or cooling systems.

The PMV model prominently features air temperature as a central input parameter. Additionally, adaptive thermal comfort models acknowledge the dynamic nature of human response to air temperature changes. In addition, the adaptive comfort model proposed by Nicol and Humphreys [29] emphasizes the significance of considering seasonal and regional variations in air temperature to accurately predict occupants' comfort.

Numerous approaches, exhibiting varying degrees of accuracy, have been formulated to assess thermal comfort within buildings [30]. Predicting thermal comfort poses complexity, due to the necessity of accounting for a multitude of environmental and personal factors.

This study will be confined to the objective dimension, employing the PMV-PPD index as the most appropriate approach to evaluate thermal comfort in non-free-run buildings.

2.1.1. PMV-PPD Index

The most widely recognized and prevalent approach is the PMV-PPD method (specified in American National Standards Institute—ANSI/ASHRAE Standard 55); the present study will center on employing this methodology for the assessment of thermal comfort. This method comprehensively addresses both environmental and personal elements, with each domain encompassing multiple measurable parameters [31,32] (p. 518). As the environmental parameters are directly ascertainable through measurement devices, distinctions among these measurement tools may lead to negligible divergences in outcomes, contingent upon the precision of the measurement instruments.

The PMV approach, devised by Fanger in 1970 [33], operates on the foundation of a heat equilibrium framework. This methodology is rooted in the principle that the impacts of the ambient environment are exclusively mediated through heat dynamics and collaborative interactions between the human body and its surroundings [34]. Fanger formulated an assemblage of associations, incorporating them into the model, thereby rendering the PMV framework, comprising six distinct physical variables.

Four environmental factors encompass air temperature, mean radiant temperature (MRT), airspeed, and air relative humidity. Conversely, personal attributes include activity level and clothing resistance, as stipulated by ASHRAE-55 [9]. Widely adopted international standards like ASHRAE or ISO 7730 endorse this approach for assessing thermal comfort conditions in free-run buildings and air conditioning ones [9,19].

The predicted mean vote (PMV) predicts the average of many peoples' votes on a thermal perception scale. The thermal perception scale comprises the following gradations: 'hot', with a score of +3; 'warm', with a score of +2; 'slightly warm', with a score of +1; 'neutral', with a score of 0; 'slightly cool', with a score of −1; 'cool', with a score of −2; and 'cold', with a score of −3. The PMV metric is intended to remain within the boundaries of 'neutral' (0), with an acceptable divergence of ± 0.5 as indicated on the seven-grade scale established by ASHRAE [9,33].

Based on Fanger's extensive examination of data sets in 1970, it was determined that, even under ideal conditions, around 5 percent of the population could experience dissatisfaction. As a response, the predicted percentage of dissatisfied (PPD) was introduced, serving as a quantifiable metric for thermal comfort by denoting the proportion of a significant population likely to perceive pronounced warmth or cold. In the context of the PPD index, individuals exhibiting values of −3, −2, +2, and +3 in the predicted mean vote (PMV) assessment would be classified as thermally dissatisfied [33].

2.1.2. Thermal Neutrality (Thermoneutral Temperature)

The concept of neutral thermal condition (NTC) commonly refers to a state in which the thermal environment is perceived by the human body as devoid of excessive warmth or chilliness. Within this condition, the body operates without necessitating supplementary energy expenditure for temperature regulation, and individuals typically experience comfort without requiring supplementary clothing or heating/cooling interventions [35].

Furthermore, investigations into comfort through field studies, as assessed by de Dear and Brager [28], revealed that occupants across diverse building contexts perceive a state of neutrality at temperatures that vary. This observation underscores the influence of adaptive responses on thermal comfort [28]. Feriadi and Wong conducted a study in the context of Indonesia's hot and humid tropical climate, unveiling a neutral temperature of 29.2 °C. Similarly, field studies conducted by researchers for the warm climates of Pakistan indicated a relatively elevated neutral temperature of 30 °C [36]. The thermally neutral zone pertains to the spectrum of temperatures within the proximate surroundings wherein a healthy human organism can uphold a standard body temperature devoid of the necessity to expend energy beyond its customary basal metabolic rate [37]. In accordance with research findings, the temperature span within which this nadir is observed is referred to as the realm of thermal equilibrium. For human beings, this range typically spans from 29 °C to 31 °C [38].

The neutrality of thermal conditions can fluctuate contingent on variables like humidity, air circulation, and the attire donned by individuals [39,40]. It is often used in discussions related to indoor environments, where efforts are made to design buildings and spaces that maintain a comfortable temperature range for occupants without the need for excessive heating or cooling.

Within architectural and engineering domains, attaining a state of thermal neutrality holds significance in the design of buildings that provide energy efficiency and occupant comfort [41]. This state pertains to a scenario in which the thermal environment encompassing a homeothermic organism is structured in a manner that its metabolic heat production remains unaltered, precluding both cold and heat stress-induced augmentations. The temperature range in which this minimum occurs is called the zone of thermal neutrality.

2.1.3. Thermal Comfort and the Orientation of the Building

The orientation of a building holds considerable influence on the indoor thermal comfort environment, due to its capacity to capture solar radiation incidence and the diverse impact of wind on the buildings as per their orientations [3,42].

According to Rowland and Howe [43], the orientation of a building constitutes a pivotal element of passive design strategies, particularly when it is pertinent to arid or semi-arid climates. It significantly influences the capacity to harness solar irradiance and regulate the impact of wind dynamics on the building envelope. During the warmer months, buildings oriented towards the west typically experience heightened exposure to solar radiation, limited shading, and elevated temperatures throughout the day. A parallel scenario unfolds for southern facades, whereas northward-oriented buildings tend to capture diminished solar angles [44]. Consequently, building orientation has a substantial effect on the energy load imposed for heating and cooling, consequently affecting overall energy consumption within the building [45]. It is essential to acknowledge that, while these principles hold general validity, there are specific exceptions according to different climatic and geographical attributes. Hence, a comprehensive examination of the ramifications of building orientation on thermal comfort assumes paramount importance for the realization of effective environmental design within built spaces.

In particular climatic contexts such as hot and arid or cold climates, the orientation of buildings must consider the path of the sun's ecliptic. In humid climates, where thermal comfort is derived primarily from air movement, optimal building orientation corresponds to the direction of prevailing winds [46]. Hence, the main building facade is ideally preferred to be positioned on the northern–southern sides, allowing minimal ingress of

solar rays through the facades and apertures during warmer seasons. This configuration mirrors the principle observed during winter, when the sun's lower altitude facilitates enhanced access to solar radiation [47].

2.2. Methodology

The study used the quantitative method in the methodology and applied comparative analysis to reach the conclusion. This was undertaken through collecting data from the site in the form of direct observations to evaluate thermal comfort conditions inside selected buildings. Therefore, a case study methodology was conducted in the current study. Moreover, the research used comparative analysis to determine the limits of thermoneutral temperature inside the buildings in the summer and winter. Before suggesting any solutions, an exhaustive comprehension of the neutral thermal condition within dwellings situated in subtropical steppe (BSH) climates was required. This helped to find the targeted function for heating/cooling systems designers and to decide possible alternatives for better thermal achievement inside the buildings. If not accurately determined, the thermal performance within the buildings could have been unclear, potentially resulting in the use of inefficient thermal solutions in the study area. Moreover, understanding thermoneutral temperature limits could potentially provide insights for designing upcoming residential developments in the region.

2.2.1. Description of Case Study

The study region is referred to as 'Garmian', a term that translates to "the warm region" in Kurdish. As per the Köppen classification, this study locale is positioned in the southeastern part of Iraqi Kurdistan and falls into the subtropical steppe (BSH) category [4,48].

Houses play a substantial role in the housing sector, projected to account for approximately 67% of the overall energy usage within the global building sector by 2030 [1]. Row houses prevail in the Garmian area [49]. Hence, the approach of a case study methodology was employed and row house typology was selected to be addressed within this research.

Hence, as a result, thirty-two air-conditioned row houses situated in the New Kalar Community within Kalar, specifically in the Garmian region, were chosen as the subject of investigation. These row houses constitute a significant 65.7% of the entire housing landscape in the study region, according to the Kurdistan Region Statistics Office [49]. These selected buildings were evenly distributed across four primary orientations, with eight houses facing each direction—south, north, east, and west.

The sample of buildings that were selected underwent a meticulous selection process in accordance with specific criteria. These criteria encompassed the equitable division of the case study buildings into four principal orientations, ensuring comparable micro-climatic attributes across the building locations. Furthermore, uniformity was sought in terms of building construction materials, exterior surface color, and building age, as well as architectural form, functional purpose, design, and prototype (see Figure 1).

Moreover, the number of occupants in one unit affects thermal comfort evaluation, as increasing the number of occupants increases the production of heat from the bodies to the surrounding environment, which raises the heat levels inside the building [46]. Therefore, the number of occupants in each house was restricted to between three and five people. Also, because of the personal factor in evaluating PMV-PPD, several criteria have been considered, such as the similarity of the ages of the occupants and gender equity, because these factors affect personal factors like clothing and metabolic rate or activities, which then affect, eventually, the evaluation process [9,33]. These criteria limited the selection of the participant numbers for the case study.

Five different observations were conducted within various sections of each house for every orientation. Therefore, a total of one hundred and sixty on-site observations were conducted within the buildings throughout the summer season (August), with the same number of observations taken in winter (January) at similar times of the day. The

observations covered different spaces inside each row house, including bedrooms, the kitchen, the living room, and guest rooms (see Figure 1a).

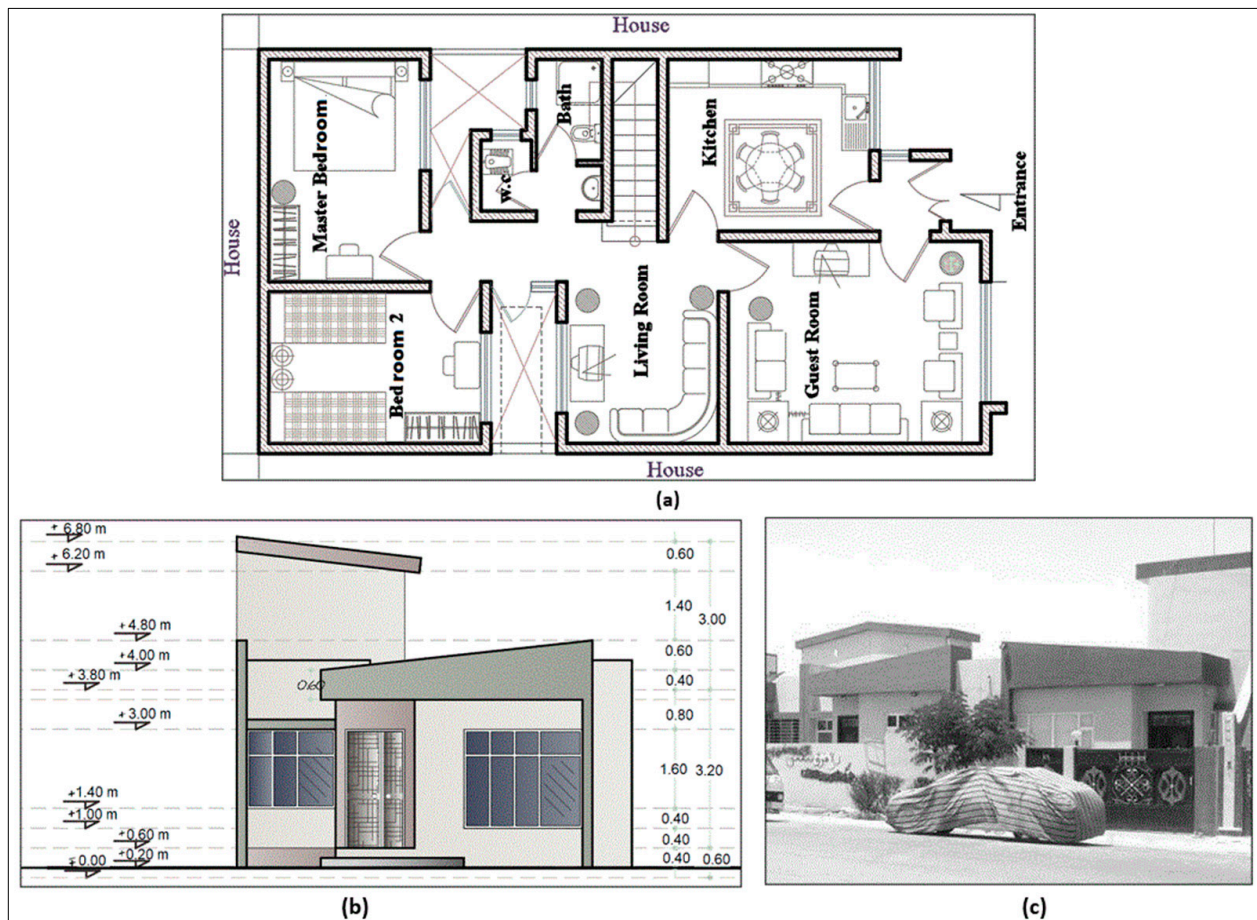


Figure 1. The case study buildings description: (a) one-floor row houses plan with a 109 m² total building area; (b) the façade (elevation) detailing, and (c) the buildings' existing condition from outside.

2.2.2. Assessment Tools and Observations Methods

The study attempts to investigate the relationship between thermoneutral temperature limits and building orientations. As one of the most professional and accessible online tools for these types of studies, the Center for the Built Environment (CBE) Thermal Comfort Tool-2017 has been supplied as a computer tool to measure the empirical elements of the calculation to estimate PMV-PPD in this study. In each observation, the following parameters were identified:

- TG: globe temperature (with 40 mm globe diameters); according to ASHRAE-55, the measurement should be at least one meter away from the walls.
- At and Rha: the interior air temperature and relative humidity, respectively, in the building, as determined using the Psychrometric (air temperature) approach with the CBE Thermal Comfort Tool.
- The metabolic rate (MET) or level of activity is calculated based on the observation area, and summer clothing insulation was taken into account as 0.5–1.03 (Clo) for summer and winter respectfully, based on the site survey and ASHRAE-55 [9].
- Airspeed (Va): an anemometer was used to measure the speed of air in the buildings in meters per second. See Table 1.

Table 1. The equipment and the specific values of parameters to obtain PMV-PPD in the study using the CBE Thermal Comfort Tool.

No.	The Parameters	Equipment	Positions	Clo Summer	Clo Winter	Metabolic Rate (Met)
Environmental						
1	Globe temperature (TG)	EXTECH-H30, Globe Thermometer (40 mm globe diameter).	Inner space of the building			
2	Air temperature (At)	‘HAMA’, an electronic weather station.	Inner space of the building			
3	Relative humidity (Rha)	‘HAMA’, an electronic weather station.	Inner space of the building			
4	Airspeed (Va)	Model DA02 of an anemometer.	Inner space of the building			
Personal						
5	The activity level and insulation level of clothing		Guest rooms	0.5	1.03	1.0
			Living rooms	0.5	1.03	1.0
			Kitchens	0.5	1.03	1.6
			Master and second bedrooms	0.5	1.03	0.8

3. Results and Discussion

As mentioned previously, 320 results were obtained—160 in each season—to evaluate thermal comfort inside the buildings in the study region using the PMV-PPD index. Forty observations for each group of eight buildings in each orientation were made—five observations in each house. Based on the fundamental principle of the central limit theorem, the minimum acceptable size for valid statistical analysis is 30 [50].

3.1. Results from the Summer

Fifty-eight observations that achieved thermoneutral environment levels inside the buildings were identified in summer for each group of houses, according to their orientation. See Table 2.

Table 2. The number of observations that reached thermoneutral levels inside the row houses in the summer for each orientation.

No.	Ta	TG	Va	PMV	PPD	Prediction	Building Orientation
1	27.7	27.3	0.04	0.4	0.08	Neutral	South
2	27.4	28.6	0.02	0.05	0.08	Neutral	
3	28	27.4	0.09	0.41	0.08	Neutral	
4	28.7	28	0.01	−0.2	0.06	Neutral	
5	28.3	27	0.05	0.45	0.09	Neutral	
6	29	28.3	0.04	−0.07	0.05	Neutral	
7	28	26.9	0.04	0.35	0.08	Neutral	
8	28.6	28.1	0.06	−0.25	0.06	Neutral	

Table 2. Cont.

No.	Ta	TG	Va	PMV	PPD	Prediction	Building Orientation
9	27.9	27	0.04	0.38	0.08	Neutral	North
10	29	28.2	0.07	−0.15	0.05	Neutral	
11	27.5	26.9	0.03	0.33	0.07	Neutral	
12	29.1	28.2	0.05	−0.13	0.05	Neutral	
13	27.7	27.1	0.04	0.39	0.08	Neutral	
14	28.8	28.3	0.03	−0.14	0.05	Neutral	
15	27.8	27.1	0.03	0.36	0.08	Neutral	
16	28.7	28.2	0.03	−0.16	0.06	Neutral	
17	27.3	26.3	0.1	0.07	0.05	Neutral	
18	27.4	26.2	0.06	0.06	0.05	Neutral	
19	27.1	26.1	0.04	0.02	0.05	Neutral	
20	27.5	26.5	0.07	0.13	0.05	Neutral	
21	27.3	26.3	0.05	0.04	0.05	Neutral	
22	27.4	25.9	0	0.1	0.05	Neutral	
23	27.2	26.6	0.09	0.09	0.05	Neutral	
24	27.1	26.4	0.03	0.07	0.05	Neutral	East
25	26.7	26	0.05	−0.1	0.05	Neutral	
26	28	27.5	0.02	0.49	0.1	Neutral	
27	29	28.7	0.02	0.08	0.05	Neutral	
28	26.9	26.1	0.05	0	0.05	Neutral	
29	29	28.3	0	0.02	0.05	Neutral	
30	26.9	26.3	0.04	0.06	0.05	Neutral	
31	29.2	28.5	0	0.13	0.05	Neutral	
32	26.7	26	0.04	−0.05	0.05	Neutral	
33	27.8	27.3	0.04	0.45	0.09	Neutral	
34	28.9	28.4	0.01	0	0.05	Neutral	
35	26.7	26.2	0.07	0.04	0.05	Neutral	
36	28.9	28.6	0	0.05	0.05	Neutral	West
37	26.6	26.2	0.01	−0.08	0.05	Neutral	
38	28	27.3	0.07	0.42	0.09	Neutral	
39	28.8	28.3	0	−0.02	0.05	Neutral	
40	26.9	26.1	0.01	0.02	0.05	Neutral	
41	27.7	27	0.06	0.37	0.08	Neutral	
42	28.9	28.6	0.05	0.04	0.05	Neutral	
43	27.9	27.5	0.05	0.45	0.09	Neutral	
44	28.2	27.8	0.03	−0.32	0.07	Neutral	
45	27.6	27.1	0.05	0.32	0.07	Neutral	
46	28.5	28	0.01	−0.2	0.06	Neutral	
47	27.8	27.3	0.07	0.4	0.08	Neutral	
48	28.2	27.4	0.03	−0.49	0.1	Neutral	

Table 2. Cont.

No.	Ta	TG	Va	PMV	PPD	Prediction	Building Orientation
49	27.7	27.1	0.04	0.33	0.07	Neutral	
50	28.4	27.7	0	−0.27	0.06	Neutral	
51	28.1	27.3	0	0.48	0.1	Neutral	
52	28.4	28	0.03	−0.25	0.06	Neutral	
53	27.4	27	0.06	0.25	0.06	Neutral	
54	28.8	28.1	0	−0.08	0.05	Neutral	
55	28	27.3	0.05	0.39	0.08	Neutral	
56	28.8	28.4	0.08	−0.15	0.05	Neutral	
57	27.9	27	0.02	0.35	0.08	Neutral	
58	28.4	27.9	0.01	−0.28	0.07	Neutral	

Based on the outcomes of the results in Table 2, the results show that the inner thermoneutral air temperature ranges in each orientation for the coldest and hottest seasons were different. For instance, in the warmer season (August), the required inner air temperature to achieve a thermoneutral condition in the southward-oriented buildings ranged between 27.4 °C and 29.1 °C, while, for the northward-oriented buildings, it was between 27.1 °C and 27.5 °C. In the same context, the range of inner air temperatures to reach thermoneutral conditions for eastward-oriented and westward-oriented buildings ranged between 26.6 °C and 29.2 °C, and between 27.4 °C and 28.8 °C. Therefore, this involved determining the highest necessary indoor temperature to establish an effective thermally comfortable environment in various orientations during the summer. For instance, the range of air temperature inside the eastward-oriented houses showed wider variety when reaching neutral thermal (thermoneutral) conditions. Also, a thermoneutral environment could be achieved with the highest temperature on this side (29.2 °C). It is important to mention that the globe temperature (TG), which was affected directly by the radiation, and the airspeed (Va) both have significant effects on the results of the PMV-PPD index, and both factors are affected by the orientation of the buildings [51]. However, the results signified that a higher temperature could be set for active systems, and consequently, lower amounts of energy could be consumed for cooling active systems. This indicates the flexibility of this orientation over the other ones in providing a good range of thermoneutral environmental conditions in summer (see Figure 2).

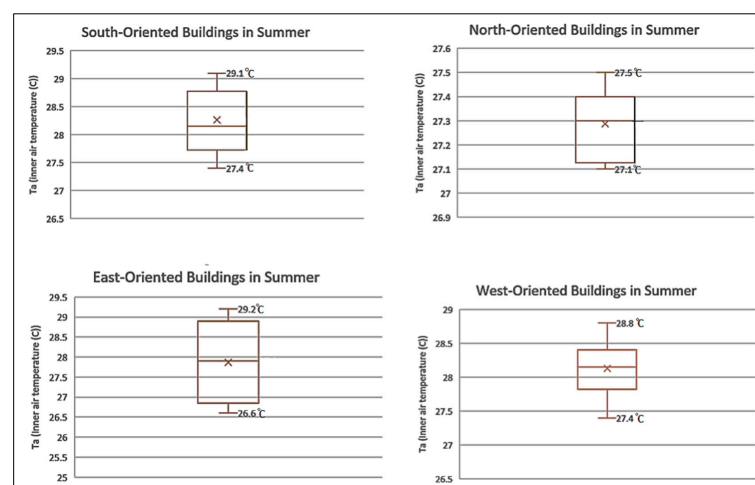


Figure 2. The range of inner air temperatures for achieving thermoneutral conditions inside the buildings in each direction in summer.

Moreover, a predicted percentage of dissatisfied (PPD) in the westward orientation was observed within the neutral thermal environment. The results demonstrated similarities but insignificant variety in PPD values, as seen in Table 3.

Table 3. The PPD level in all the directions inside the building within the neutral thermal environment in summer.

Orientations	Max. Thermoneutral Temp.	Min. Thermoneutral Temp.	Average PPD
South	29.1	27.4	0.07
North	27.5	27.1	0.05
East	29.2	26.6	0.06
West	28.8	27.4	0.07

Table 3 demonstrates that the western and southern sides had the higher PPD value, which was 7%, and the northern side had a lower PPD value of 5%.

3.2. Results from the Winter

In the same context, forty observations of neutral thermal levels inside the buildings in winter were pointed out, as seen in Table 4.

Table 4. The number of observations that achieved neutral thermal levels inside the row houses in the winter.

No.	Ta	TG	Va	PMV	PPD	Prediction	Building Orientation
1	20.2	16	0	0.09	0.05	Neutral	South
2	20.5	17.10	0	0.13	0.05	Neutral	
3	20.1	15.9	0	0.06	0.05	Neutral	
4	19.9	16.5	0.01	0.02	0.05	Neutral	
5	20.6	17.5	0.01	0.16	0.06	Neutral	
6	20	15.90	0	0.05	0.05	Neutral	
7	20.1	17.4	0.01	0.13	0.05	Neutral	
8	20.2	17	0.01	0.1	0.05	Neutral	
9	19.5	19.1	0	0.2	0.06	Neutral	North
10	19.8	19.2	0	0.24	0.06	Neutral	
11	19.9	19.4	0	0.26	0.06	Neutral	
12	19.5	18.8	0	0.18	0.06	Neutral	
13	19.7	19	0	0.21	0.06	Neutral	
14	19.8	19.1	0	0.23	0.06	Neutral	
15	20	19.5	0	0.28	0.07	Neutral	
16	19.4	19.4	0	0.16	0.06	Neutral	
17	21.1	19.6	0	0.4	0.08	Neutral	East
18	21	19.5	0	0.39	0.08	Neutral	
19	21.5	20.2	0	0.49	0.1	Neutral	
20	21.4	20.1	0	0.48	0.1	Neutral	
21	21.4	19.4	0	0.42	0.09	Neutral	

Table 4. Cont.

No.	Ta	TG	Va	PMV	PPD	Prediction	Building Orientation
22	21.5	19.8	0	0.46	0.09	Neutral	West
23	21.4	19.8	0	0.45	0.09	Neutral	
24	21.3	19.7	0	0.43	0.09	Neutral	
25	22.1	21	0	−0.4	0.08	Neutral	
26	21.5	19.9	0.01	0.44	0.09	Neutral	
27	22.2	20.9	0	−0.39	0.08	Neutral	
28	21.7	19.7	0	0.47	0.1	Neutral	
29	22.1	20.6	0	−0.44	0.09	Neutral	
30	21.6	19.8	0.01	0.44	0.09	Neutral	
31	22.4	21.1	0	−0.34	0.07	Neutral	
32	21.7	19.6	0	0.46	0.09	Neutral	
33	22.3	21	0	−0.37	0.08	Neutral	
34	21.4	19.8	0.01	0.42	0.09	Neutral	
35	22.2	20.8	0	−0.41	0.08	Neutral	
36	21.9	19.6	0	0.48	0.1	Neutral	
37	22.1	20.8	0	−0.42	0.09	Neutral	
38	21.6	19.5	0.01	0.41	0.08	Neutral	
39	22.3	21	0	−0.36	0.08	Neutral	
40	21.8	19.8	0	0.49	0.1	Neutral	

As illustrated in Table 4, in the winter season (January), the outcomes showed different ranges of inner air temperature for arriving at thermoneutral conditions inside the buildings. For the houses with a southward orientation, the range of inner air temperature was between 19.9 °C and 20.6 °C, whereas, in the northward-oriented houses, the range was between 19.4 °C and 20 °C. Furthermore, the range in the houses for the eastward-oriented houses was between 21 °C and 21.5 °C, and, inside the westward-oriented houses, the range was 21.4 °C and 22.4 °C. The outcomes revealed that, in winter, the minimum required air temperature inside the building in the northward orientation to reach a thermally neutral level was 19.4 °C. Thus, the minimum required air temperature to be set for the heating active systems in each orientation to maintain better range of thermoneutral environment conditions in winter was identified (see Figure 3).

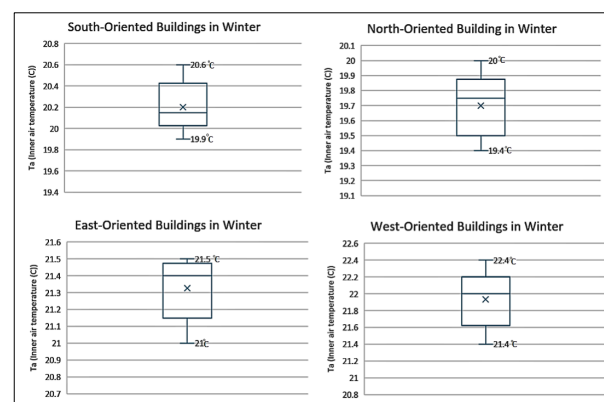


Figure 3. The range of indoor temperature fluctuations necessary to create a thermoneutral environment in buildings during the winter for all orientations.

Also, PPD in winter was tested for all the orientations. Again, the differences were insignificant among the different orientations, as seen in Table 5.

Table 5. The degree of PPD in all the directions of the buildings under neutral thermal environment conditions during winter.

Orientations	Max. Thermoneutral Temp.	Min. Thermoneutral Temp.	Average PPD
South	20.6	19.9	0.05
North	20	19.4	0.06
East	21.5	21	0.09
West	22.4	21.4	0.09

As expressed in Table 5, the differences in PPD were very small and the maximum PPD was 9% in the eastern and western sides, while the lower PPD was 5% in the southern side.

3.3. Discussion

The analysis of the correlation between indoor air temperature and thermally neutral environment showed that the upper inner air temperature to reach the comfort limit in the summer was 29.2 °C and the lower limit was 26.6 °C, in air-conditioned buildings in the study region. However, in the winter, the upper air temperature required to achieve thermoneutral conditions was 22.4 °C, and the lower air temperature limit was 19.4 °C. Hence, if we take a whole year, the range of inner air temperature limits in the study area to achieve a thermoneutral environment ranged between 19.4 °C and 29.2 °C.

These results can help the designers, building physics specialists, and HVAC professionals make more accurate decisions in order to avoid thermal discomfort inside the buildings and improve well-being, productivity, and occupants' overall health. Also, the study outcomes showed a wider acceptable range of temperature for achieving a thermoneutral environment in summer in the eastward orientation (26.6 °C to 29.2 °C). This outcome could help the architects, planners, and authorities to make the right decision regarding the orientation and the design of the buildings.

The comparison of these results with other studies in some adjacent or surrounding areas shows some similarities and differences. For example, a study was carried out in Tehran (Iran) during summer, which demonstrated that the thermal comfort temperature inside the buildings was 26.2 °C [52]. Another study was conducted in Baghdad (Iraq), and the results showed that the limits of inner air temperature for thermal comfort conditions were between 19.0 °C and 29.0 °C [8]. However, Heidari and Sharples [53] studied the comfort temperature levels in summer and winter in Ilam (Iran) and found that the temperature limits inside residential buildings to achieve thermal comfort were between 20.8 °C and 28.4 °C. Despite these studies offering valuable insights into the limits of the air temperature for reaching thermal comfort thresholds inside buildings in hot regions in neighboring countries, they fail to give an accurate comprehension of the air temperature limits required to achieve a thermoneutral environment as a design model suitable for assessing the thermal comfort boundaries of residents in houses in the study area.

Finally, the outcomes of the current study introduce a range of recommendations based on empirical data for controlling and regulating the temperature inside buildings and on the orientation of buildings, to develop energy-efficient building designs and to make them more comfortable thermally. The vision of this study contributes to having comfortable, more sustainable, and environmentally friendly buildings.

4. Conclusions

The importance of air temperature in evaluating thermal comfort within buildings cannot be overstated. The selection and maintenance of appropriate air temperature ranges directly impact thermal neutrality, which affects occupants' well-being, and energy effi-

ciency in buildings. By understanding the thermally neutral condition, acknowledging its influence on occupants' satisfaction and productivity, and recognizing the energy efficiency implications, architects and engineers can create indoor environments that prioritize comfort and sustainability.

In this research, a thermal comfort evaluation using the PMV-PPD index method was carried out to establish a model defining the range of indoor air temperatures necessary to determine the thermoneutral conditions within residential buildings. It was crucial to investigate the relationship between thermoneutral thresholds and the required limits of inner air temperature in the building. Additionally, the study tried to investigate how the orientation of buildings affected these boundaries.

The study region is located in the subtropical steppe climate of Garmian in Northern Iraq. A case study methodology was applied to find the results, and direct site observations and office work with the aid of software (CBE Thermal Comfort Tool-2017) were conducted for this purpose. The findings indicated that, during the summer, the upper limit for indoor air temperature was 29.2 °C, while, during the winter, the lower limit was 19.4 °C. These temperature ranges represent the overall inner temperature limits required to implement thermally neutral levels for the Garmian region in Northern Iraq. Moreover, the result of the study signifies the role of the orientation of the buildings and the seasons in changing the indoor air temperature limits to reach a thermoneutral environment inside the buildings. However, the results indicate that buildings with an eastward orientation exhibit the highest thermal flexibility. This is attributed to the considerable temperature variation within the thermoneutral zones during both extreme seasons, as seen in Table 6.

Table 6. The role of building orientation and the season on the indoor air temperature to achieve a thermoneutral environment.

Buildings Orientations	Upper Thermoneutral Temp. °C	Lower Thermoneutral Temp. °C	Upper Thermoneutral Temp. °C	Lower Thermoneutral Temp. °C
	Summer		Winter	
South	29.1	27.4	20.6	19.9
North	27.5	27.1	20	19.4
East	29.2	26.6	21.5	21
West	28.8	27.4	22.4	21.4

These results are applicable to air-conditioned residential buildings in the region of the study, and suggest a new standard to designers for heating/cooling active system design. It is important to mention that integrating knowledge of temperature constraints into the design phase empowers architects and engineers to craft environments that deliver maximum comfort, reduce energy usage, and harmonize with the desires and requirements of the occupants. This is undertaken by setting the active cooling system within these specific ranges, which commonly change based on the season and the building orientation.

Despite the general similarities and insignificant differences in PPD values, the PPD value in winter was recorded as slightly higher than in summer on three sides of the buildings, except for the southward orientations. The design of the buildings, the natural ventilation, and the humidity level inside the buildings are significant environmental factors driving this issue [9]. Therefore, the study recommends more investigations to study the relationships of these factors with this phenomenon. Moreover, building self-shading can play a significant role in reducing the requirement levels of active systems and improve energy efficiency in buildings without compromising the thermal comfort of the occupants. Hence, future study in this field is recommended and the comparison will help researchers to comprehensively understand the differences in energy consumption in these buildings.

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