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Microclimatic analysis of outdoor thermal comfort of high-rise buildings with different configurations in Tehran: Insights from field surveys and thermal comfort indices

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ABSTRACT

This study investigates the microenvironment of open-air settings in Tehran, Iran, and explores the relationship between different thermal comfort indices, including PMV, PET, and TSV. The research was conducted in district 22 over a 16-day period using microclimatic measurements and questionnaire surveys. The analysis of 680 questionnaires provides valuable insights into the most and least comfortable thermal conditions and the limitations of PMV in assessing thermal sensations above 30 °C in several scenarios. The study recommends the use of non-linear regression formulas in anticipating thermal comfort during excessively hot circumstances and emphasizes notable distinctions between the primary heat stress classifications and the ones established in this research. The study suggests the need for revising heat stress classifications to assess outdoor thermal conditions in Tehran. The research also acknowledges the complexity of outdoor thermal satisfaction and recommends future studies that delve into the influence of diverse parameters on outdoor thermal comfort in distinct seasons.

1. Introduction

Projections indicate that the trend of global urbanization will persist in the future and, in addition to the expansion of urbanization, it has led to the aggravation of urban heat islands (UHI) [1–5]. This effect refers to the higher temperatures in cities compared to rural areas, which is due to a combination of urban expansion and the influence of global warming on the microclimate [2]. The complexity of the UHI is shaped by various factors including urban development and building structures [6], and its impact on human health and well-being should not be underestimated [7]. In this line, it looks essential to understand the relationship between urbanization and the UHI for the purpose of promoting sustainable urban management.

Thermal comfort, defined as an individual's subjective assessment of satisfaction with the outdoor temperature and environment [8,9], is contingent upon a multitude of factors in outdoor spaces. These factors encompass air temperature (Ta), humidity (Rh), wind speed (Ws), Mean radiant temperature (Mrt), metabolic heat (*Met*), and clothing insulation (Iclo). Assessing thermal comfort in the outdoors requires an examination of the microclimate, as well as the physiological and behavioral elements that contribute to the overall experience [10–12]. In this regard, to accurately assess thermal comfort, it is crucial to consider both the microclimate conditions and the individual's physiological and behavioral characteristics accurately assess thermal comfort [13].

In recent years, the assessment of thermal comfort has become a matter of heightened interest due to the influence of climate change and the growing issue of heat stress in urban environments [11,14–16]. Examination of how the distance between urban blocks affects thermal comfort in outdoor environments has been changed as a significant research topic in recent years, with interesting studies being conducted to explore this aspect. According to a study conducted by Ref. [17], the effect of urban canyons on outdoor thermal comfort was compared

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based on different street widths (10, 15, 20, and 25 meters) and orientations (East-West and North-South). The research found that during the winter solstice on December 21st, the East-West canyons did not receive direct sunlight, while they received direct sunlight during summer and at morning and afternoon times. Conversely, during the shortest day, the North-South canyons experienced some sun exposure for a short period, even in the narrowest canyon, and were entirely exposed to the sun during the mornings and afternoons. The Badaguan District in Qingdao, a Historical Preservation Area (HPA), was investigated in terms of microclimate and the thermal environment by Ref. [18]. The study employed field measurements and simulation techniques to evaluate three scenarios: the existing conditions, a reduction in green space, and an increase in building density. The research revealed that diverse street parameters affect microclimate differently and that both decreasing green space and augmenting building density have an adverse effect on the thermal environment. Moreover, the proportion of building height to the distance between them (H/W) is considered to be a contributing factor in altering the immediate environmental surroundings [19]. For example, in an urban area with high population density, researchers [20,21] explored how the structure of buildings relates to thermal comfort. Their analysis led them to suggest that shortening the length of buildings and increasing ventilation on lower floors could serve as a viable approach for reducing heat levels at the pedestrian level. Earlier studies carried out by researchers [22,23] employed the ENVI-met microclimate model to explore outdoor thermal comfort in Ghardaia, a region characterized by a hot and dry climate. The investigations revealed that the orientation of the urban canyon has a significant influence on thermal comfort. Specifically, adjusting the ratio of building height to canyon width (H/W) was observed to cause a slight decrease in air temperature and an improvement in the predicted mean vote (PET) for thermal comfort. [24]. conducted a comprehensive investigation on the effect of the height-to-width ratio on pedestrian thermal comfort in the hot and humid climate of Singapore, utilizing Envi-met software. The findings of the study revealed that a height-to-width ratio of 3 or higher is significantly associated with optimal thermal comfort conditions for pedestrians. The study conducted by Ref. [25] focuses on the thermal comfort conditions in a linear housing layout located in an arid climate with hot summers and cold winters. The researchers explore the impact of two variables, H/W ratio and residential block orientation, on three environmental factors - Ta, Tmrt, and PET. The study findings suggest that adjusting the H/W ratio can effectively improve thermal comfort conditions. Increasing the H/W ratio from 1 to 1.5 leads to a reduction in the average Ta, Tmrt, and PET during summer, while changing the H/W ratio from 0.5 to 1 is the best option for winter. Moreover, an orientation angle of 135° is recommended for residential blocks to achieve optimal thermal comfort conditions in both seasons.

Based on the reviews mentioned earlier, it can be concluded that the space between residential complexes provides ample opportunities for different activities, such as walking, cycling, socializing, and relaxing, among others. Thus, it is crucial to establish thermal comfort in this area. In Iran, most houses and apartments are built in a linear style, with one building abutting the next due to street expansion and paving. As a result, residential complexes tend to have a similar architectural style. Thus, the primary objective of the study was to investigate the correlation between thermal comfort indices, namely Predicted Mean Vote (PMV) and Physiological Equivalent Temperature (PET), with field survey data obtained from different types of linear buildings include of SC1 (singular blocks E-W), SC2 (singular blocks N-S), SC3 (linear blocks E-W), and SC4 (linear blocks N-S).

Following an examination of various urban configurations and their impact on the urban environment, this study has aimed to analyze the applicability of different thermal comfort indices for assessing outdoor thermal environments in the built areas of Tehran, which is located in an arid/desert climate with cold winters.

2. Material and methods

2.1. Climate features of the study area: city of Tehran

Tehran, the capital of Iran, lies at 51°19 E, 35°41 N [26], with the Alborz Mountains to the north and a central desert to the south, resulting in significant elevation and climate differences between the city's northern and southern regions [27]. The Köppen climate classification system categorizes Tehran's climate as cold semi-arid [28], with mild weather in spring and fall, hot and dry summers, and cold winters [29]. The average yearly air temperature, measured at Mehrabad meteorological station, is 17.5 °C, ranging from 3.8 °C in January to 29.5 °C in August [30]. District 22, indicated by a black circle in Fig. 1 showing Tehran's land surface temperature in July 2010 [31], was chosen for analysis in a research study. The district is located on the track of prevailing westerly winds and is the first district developed according to urban sustainability principles [32]. However, with the increasing construction of dense tall buildings, and decreasing the green areas the sustainability and livability of the district are deteriorating year by year and leading to be one of the most dangerous areas in terms of UHI in Tehran [33].

2.2. Outline of selecting cases

After examining the impacts of various urban configurations on the urban environment, this study aims to analyze the applicability of different thermal comfort indices for evaluating outdoor thermal environments in the built areas of Tehran. To achieve this objective, the research team has established a four-step approach for the study:

The first step of this research was to identify suitable locations for this study. The researchers analyzed the common configuration in Tehran and selected four different configuration (singular blocks E-W (SC1), singular blocks N-S(SC2), Linear blocks E-W(SC3) and Linear blocks N-S (SC4) based on previous studies [27,34,35]. The configurations selected in this study differed in their lengths, widths, and heights. In this context and according to the definition of tall buildings in Tehran [36], the chosen configuration for the selected building was set at a height of 48 meters as the minimum height of tall buildings. Moreover, according to the discussions and the rules listed in CTBUH [37,38], the minimum length and width suitable for tall buildings are derived from Eq (1). Where, H and D are Height and Diameter respectively (Fig. 2).

$$\frac{\mathbf{H}}{\mathbf{D}} \geq \mathbf{1.5} \times \mathbf{3.14} \qquad \text{Eq. (1)}$$

Additionally, the optimal distance between buildings of 24–60 meters should be at least 10 meters for suitable ventilation based on the [19], the selected forms in this study were considered with a height of 48 meters, length, and width of 10 meters, and a 10-m distance between them.

In the second step of this study, research team were looking for suitable places in accordance with the discussions in the previous section. In this regard, selected case studies from the 22nd district of Tehran due to the strong influence of UHI were chosen (Fig. 1) [39]. In selecting the samples, care has been taken to ensure that all the cases have the same parameters affecting UHI, namely numbers of buildings, density, height, the ratio of opening to façade –window to wall ratio-, floor height, and function), pavement (type of material, albedo, conductivity, thickness, volume heat capacity). In the next step, the researchers investigated the effect of different urban configurations on different indicators of thermal comfort in the field. In the last step of this study, the thermal comfort indices (PMV and PET) were compared to field survey data. The purpose of this phase was to evaluate the suitability of various thermal comfort indices for assessing outdoor thermal environments in semi-arid climates in Iran. The established goals can help architects improve sustainability conditions by guiding their decision-making in designing high-rise buildings to reduce the UHI

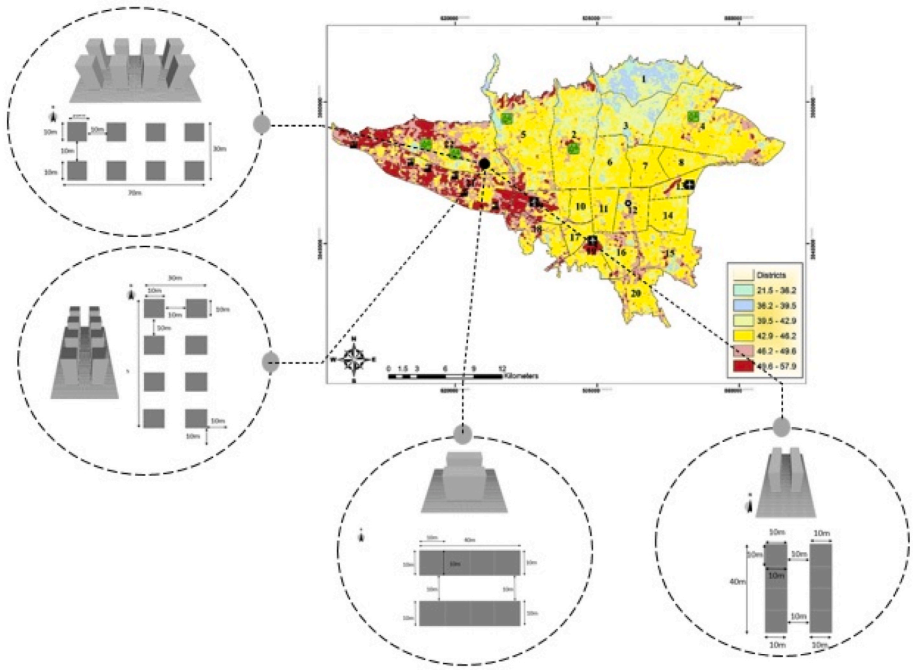

Fig. 1. Illustrates map of land surface temperature of Tehran, July 2010 and the black circle in district 22 represents the selected location for analyzing [31].

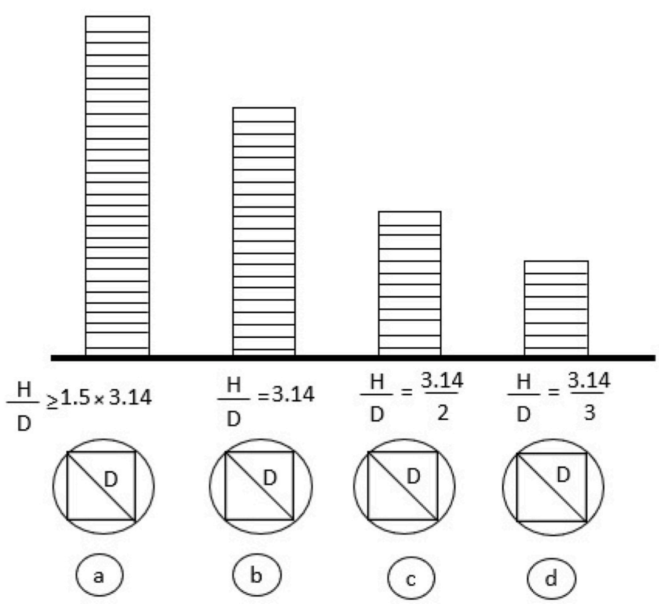

Fig. 2. How to get the length and width of a tall building [37].

effect. This study provides a framework for the research team to assess the influential criteria and determine the most effective strategies for reducing the UHI impact. This can lead to the development of more environmentally friendly and energy-efficient building configurations. The research diagram has been shown in Fig. 3.

2.3. Field measurement and survey sites

From July 12th to July 27th, 2019, a series of field surveys and measurements were conducted over a 9-h period each day, commencing at 9 a.m. and concluding at 6:00 p.m. Three thermal parameters, namely air temperature (Ta), relative humidity (RH), and mean radiant temperature (Tg), were continuously recorded on a per-minute basis, while air velocity (Va) was recorded every 5 min. Additionally, a questionnaire was distributed to individuals near the measurement sites. In this field survey, every participant was initially provided with an overview of the questionnaire. After gaining a thorough understanding of the questions, the participants were then instructed to complete the questionnaire. Out of the 220 questionnaires collected in each first stage scenarios, 50 were discarded during the screening process due to incompleteness, resulting in a total of 170 valid questionnaires. The specific details of this information can be found in Table 1.

2.4. Measurement parameters and instruments

According to ASHRAE Standard 55–2017 guidelines, microclimatic parameters were measured, including air temperature (Ta), relative humidity (RH), globe temperature (Tg), and air velocity (Va). These measurements were taken near the subjects at a height of 1.1 meters in compliance with ISO 7726 [40]. To record Ta and RH, a data logger [15] was used, while Tg was measured using a JTR globe thermometer with an emissivity of 0.95. It's worth noting that it takes around 15 min for the standard globe thermometer to stabilize, which meets the investigation's requirements [41]. To measure wind velocity, a hot-wire anemometer was utilized with the capability to measure two ranges of wind speed: 0–4.99 m/s and 5–50 m/s for low wind speeds. Specifically, the instrument employed was the Kanomax Model KA22 hot-wire anemometer. The ranges and accuracy of the micrometeorological measurements are summarized in Table 2.

The operative temperature (Top) is a widely used metric in outdoor thermal comfort research for evaluating the combined impact of multiple environmental variables on human comfort. Top accounts for the effects of air temperature, mean radiant temperature, and air velocity, which are all known to influence thermal perception in outdoor settings. (Eq. (2)). This index is calculated using an equation specified by ASHRAE 55 2013 [43] and ISO7730 2005 [44], and consider multiple factors that contribute to thermal comfort. The calculation of Top provides a comprehensive assessment of thermal comfort in outdoor environments and is widely used by researchers to study human thermal response to various outdoor conditions [44,45].

$$Top = ATa + (1 - A)\, T_{mrt} \quad \text{Eq. (2)}$$

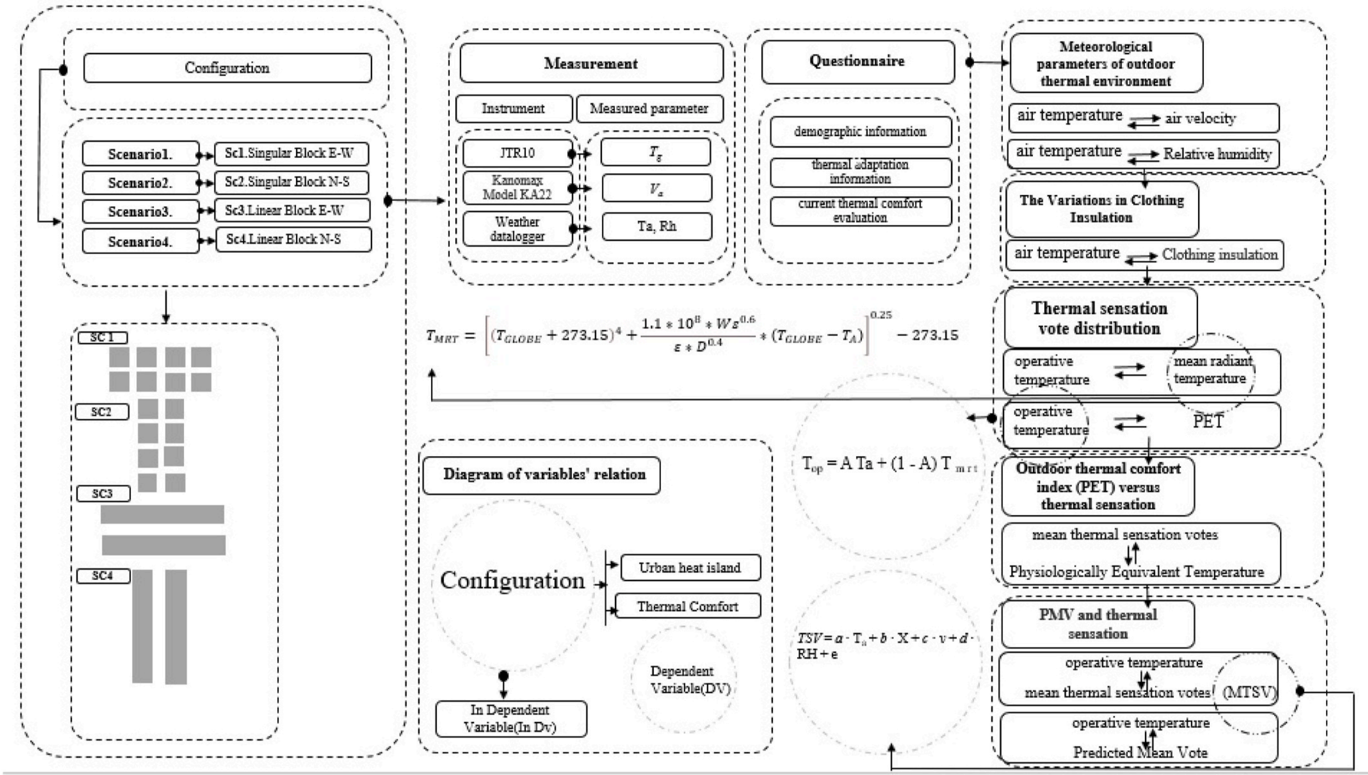

Fig. 3. Study conceptual diagram.

Table 3 presents the dependency of the mean weight coefficient (A) for Ta and Tmrt on Va, where A is calculated as the mean value of the two coefficients and reflects the combined influence of these variables.

Tmrt is a crucial factor in assessing human thermal comfort as it reflects the combined impact of short-wave and long-wave radiation. Tmrt is calculated as the temperature of an imaginary surface that emits radiation equivalent to that of the surrounding urban environment and provides an estimate of the radiation exposure experienced by individuals [47]. Tmrt was calculated according to the ISO 7726 (1998) standard [40], which deals with forced convection. This calculation was performed using the Tg, Va, Ta, emissivity of the globe (εg, assumed to be 0.95), and the diameter of the globe (D, approximately 110 mm).

$$T_{\mathrm{mrt}} = \left[(T_{GLOBE} + 273.15)^4 + \frac{1.1*10^8*Ws^{0.6}}{\varepsilon*D^{0.4}}*(T_{GLOBE} - T_A) \right]^{0.25} - 273.15 \quad \text{Eq. (3)}$$

This study also examined the total insulation of clothing, as defined in the ASHRAE Handbook (2013). Accurate measurements of clothing insulation can be obtained through the use of heated mannequins [48, 49] and active subjects [50], as reported by the Handbook. However, obtaining precise measurements of clothing insulation may prove challenging in many engineering applications. In order to calculate the combined insulation of a clothing ensemble, a formula that involves individual insulation values can be employed, following the approach described by Olesen and Nielsen in 1985 [51]. A set of insulation values for commonly worn individual garments can be obtained from the ASHRAE Handbook to use in this calculation. The formula for total insulation is represented as:

$$I_{cl} = 0,835\Sigma_i I_{clu,i} + 0/161 \quad \text{Eq. (4)}$$

Where, Iclu,i refers to the insulation of each individual garment, and Icl denotes the overall insulation of the clothing ensemble, as previously defined. An alternative, simplified formula [48] can also be used, which provides nearly accurate results:

$$I_{cl} = \Sigma_i I_{clu,i} \quad \text{Eq. (5)}$$

The field survey collected detailed information on the insulation of the clothing, while the calculation of the clothing insulation was performed using Eq (4).

Moreover, Similar to previous studies [8,52] that were conducted outdoors and included a large number of people, the activity level in this survey was not manipulated and was maintained at a constant rate throughout the research in accordance with ISO 7730 standards [53].

Predicted Mean Vote (PMV) is a thermal comfort index that utilizes a mathematical model to predict the average thermal sensation votes of a large group of individuals [54]. While it is typically used to assess thermal comfort in indoor environments, some studies have applied this index to evaluate thermal comfort in outdoor spaces as well [55–57]. The model takes into consideration various factors including air temperature, radiant temperature, air velocity, humidity, and clothing insulation [58]. The PMV was computed in this study by utilizing the software (DeltaLog10) of the device. The logs, activity, and clothing values obtained from the questionnaires were used as inputs for the calculation.

To calculate PET in this study, the RayMan software was employed. RayMan was developed by Matzarakis, and Mayer at the University of Freiburg and has been utilized in various studies to estimate the PET index, including those by Refs. [15,52,59].

The Physiological Equivalent Temperature (PET) metric utilizes the Munich Energy-balance Model for Individuals (MEMI) developed by Ref. [60]. The climatic data of Ta, RH, v, and MRT, as well as personal data such as age, height, weight, clothing, and activity, were inputted into the RayMan software to calculate the PET index [61]. Additionally, geographic data such as longitude, latitude, and altitude, along with the date and time of questionnaire completion, were also entered into the software.

Table 1
Comprehensive overview into detail of field survey.

Situation	Date	Gender	Number of subjects	Age	Participants
SC1	12,13,14,15 July 2019	Male	80	>20	5
				21–35	10
				36–50	15
				51–60	30
				>65	20
		Female	90	>20	10
				21–35	5
				36–50	40
				51–60	20
				>65	15
SC2	16,17,18,19 July 2019	Male	100	>20	10
				21–35	20
				36–50	20
				51–60	40
				>65	10
		Female	70	>20	5
				21–35	25
				36–50	15
				51–60	20
				>65	5
SC3	20,21,22,23 July 2019	Male	90	>20	15
				21–35	5
				36–50	40
				51–60	20
				>65	10
		Female	80	>20	5
				21–35	10
				36–50	30
				51–60	15
				>65	20
SC4	24,25,26,27 July 2019	Male	110	>20	10
				21–35	10
				36–50	20
				51–60	50
				>65	20
		Female	60	>20	5
				21–35	30
				35–50	5
				51–60	10
				>65	10

Table 2
Measured parameters and features of the instruments used in this research [42].

Instrument	Measured parameter	Accuracy	Range
JTR10	T_g	±0.2 °C	5–120 °C
Kanomax Model KA22	V_a	±2%	0–4.99 m/s, 5–50 m/s
Weather datalogger	Ta	±0.9 °C from 40 °C to 60 °C ±0.5 °C from 5 °C to 40 °C ±1.1 °C from −20 °C to 5 °C ± 3%	−40 °C-70 °C
	Rh	±3%	0 to 90%

Table 3
The variation in the value of coefficient A across different air velocity ranges [46].

V_a(m/s)	<0.2	0.2–0.6	>0.6
A	0.5	0.6	0.7

2.5. Questionnaire

The survey encompassed three distinct parts which included gathering demographic data, assessing thermal adaptation, and evaluating current levels of thermal comfort. The demographic information section included questions about the participants' age, gender, height, and weight. The second section focused on the participants' thermal adaptation and included questions about their thermal experience, activity type, and clothing. The objective of the third section was to collect data on the thermal comfort status of the participants. The questionnaire was created to match the thermal environment criteria outlined in ASHRAE Standard 55 (2013) and ISO 7730 (2005) standards. In earlier research, a 9-point thermal sensation scale was utilized to evaluate indoor thermal conditions, ranging from very cold (-4) to very hot (4). To account for the possibility of hot and humid conditions during the survey, the same 9-point scale was incorporated in the questionnaire for this study. During the field survey, while collecting the microclimate parameters, nearby subjects were randomly selected to participate in a questionnaire. Each subject was introduced the questions and instructed to rate their current thermal perception by marking an appropriate scale.

2.6. The empirical model of thermal sensation: understanding how we experience heat

The summary of previous studies [62,63–66] allows us to express empirical thermal sensation as Eq. (6), Where (A-E) linear regression coefficients and TA, V, and RH variables indicate air temperature (°C), wind speed (in MS-1), and relative humidity (in %) respectively. However, the value of X can differ and may either refer to global solar radiation in (W m−2) (as shown in studies by Refs. [67–69]) or mean radiant temperature (as demonstrated in studies by Refs. [64,70]. However, in this study, the research team decided to consider X based on global solar radiation in (W m−2)

$$TSV = a\bullet \mathrm{T_a} + b\bullet \mathrm{X} + c\bullet v + d\bullet \mathrm{RH} + \mathrm{e} \quad \text{Eq. (6)}$$

3. Results

3.1. Meteorological variables impacting outdoor temperature

The velocity of air (Va) has been established as a crucial factor affecting human thermal comfort in terms of thermal environment parameters. In this research, the variations of Va were documented and presented in Fig. 4. Most of the data fell within the range of 1.20–3.20 M/S, with the highest recorded value being approximately 1.36,3.2,1.67

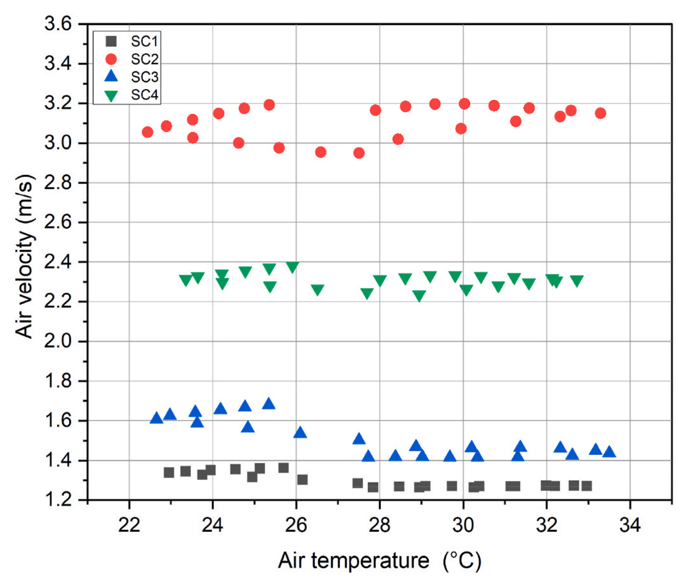

Fig. 4. Correlation of air temperature and velocity in various scenarios.

and 2.38 M/S in SC1, SC2, SC3, and SC4 respectively. This suggests that the studied locations were not generally in low wind conditions, but rather in high wind conditions. This phenomenon might be attributed to the lack of nearby structures that could act as windbreaks, leading to a higher wind speed in these areas.

The interplay between relative humidity (RH) and thermal comfort is of paramount importance in regions characterized by high temperatures and humidity levels, as demonstrated by research conducted by Ref. [71]. The data presented in Fig. 5 reveals that the levels of RH were elevated, with a majority of the readings surpassing 55%. This highlights the significance of considering RH when evaluating thermal comfort. The air temperature, in the same figure, was found to fluctuate within a range of 23.35 (CS2) 32.95 °C (CS4). This indicates that outdoor thermal conditions can sometimes become quite harsh. In order to stay comfortable and maintain good health, it is recommended to refrain from engaging in physically demanding tasks in these types of climates [72]. Furthermore, the RH decreases as air temperature increases, emphasizing the importance of considering both air temperature and RH when evaluating outdoor thermal comfort. The minimum value of RH was recorded when air temperature reached its peak value. Specifically, air temperature was higher than 36 °C from 12:30 to 17:00 in whole scenarios, reaching to more than of 33.49 °C in CS3.

3.2. The variations in clothing insulation

The effect of the insulating properties of clothing on the perception of temperature is an important aspect of maintaining thermal comfort, and it is influenced by ambient temperature (Ta) [73]. In the present investigation, the questionnaire was utilized to gather information regarding the clothing worn by each participant. The total clothing insulation was subsequently determined using Eq (5). This approach has been employed in prior studies to assess clothing insulation [66,74,75]. Fig. 6 illustrates that the insulation of the clothing ranged from 0.3 to 0.6 clo, with the highest being 0.9 clo and the lowest being 0.1 clo. The mean clothing insulation for each situation was 0.58, 0.42, 0.32, and 0.40 clo, in that order. All situations, except Sc1, had values that were below the standard 0.57 clo for summer, which is defined in ANSI/ASHRAE Standard 5 (2017). This was primarily since all subjects were dressed in casual attire.

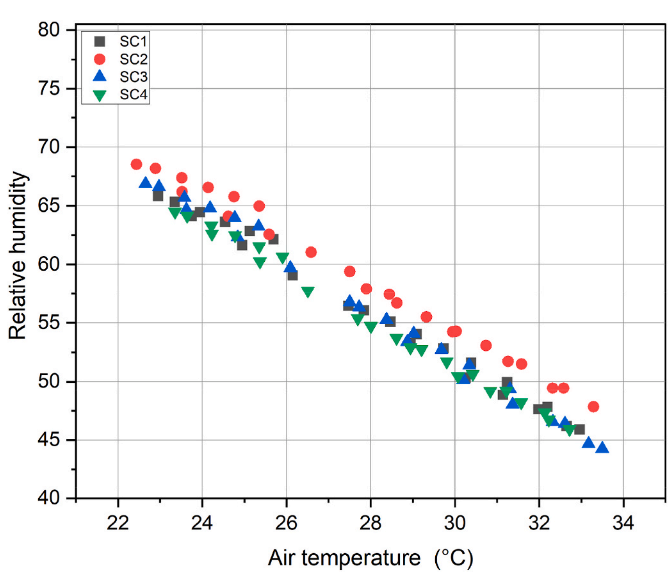

Fig. 5. Correlation of air temperature and Relative humidity in Various Scenarios.

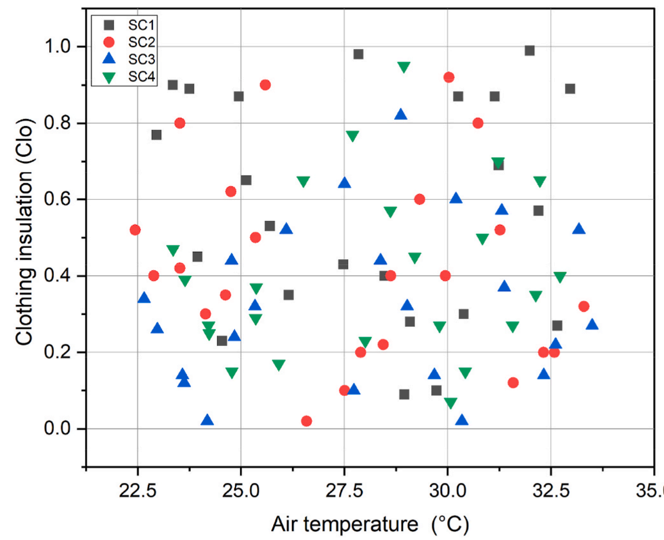

Fig. 6. Insulating Clothes for Various Temperature Conditions in whole scenarios.

3.3. Distribution of thermal sensation votes among individuals

In Fig. 7, the distribution of thermal sensation votes is presented as a percentage of the total. Most participants reported a "warm" sensation (+3), accounting for over 37% of the total votes across all scenarios. In some scenarios, between 9% (Sc2) and 31% (Sc4) of participants reported feeling "hot" (+4), which may be due to the outdoor air temperature exceeding 31 °C during the survey. The combined percentage of votes for "warm" (+3), "somewhat warm" (+2), and "hot" (+4) was over 69% across all scenarios, with the highest percentages being recorded in Sc3 and Sc4, and the lowest in Sc2. A relatively small number of participants reported feeling neutral. These findings suggest a need to improve the outdoor thermal environment in cold semi-arid regions to encourage outdoor human activities.

Moreover, Fig. 8 illustrated that MRT and PET have recorded an upward trend with the rising of Top in whole scenarios. While the gradients of distinct indices for thermal comfort exhibited considerable variation. In this study, the range of T_{op} (i.e., the highest recorded temperature) varies greatly, ranging from 20.36 to 43.69 °C. Most T_{op} points were found within the range of 32 °C–41 °C. Analysis of the collected measurement data revealed that, during the summer period, the average physiological equivalent temperature ranged from 32.35 °C to 34.5 °C across all locations, with relatively high values recorded at each site. These results suggest that, despite the rather favourable

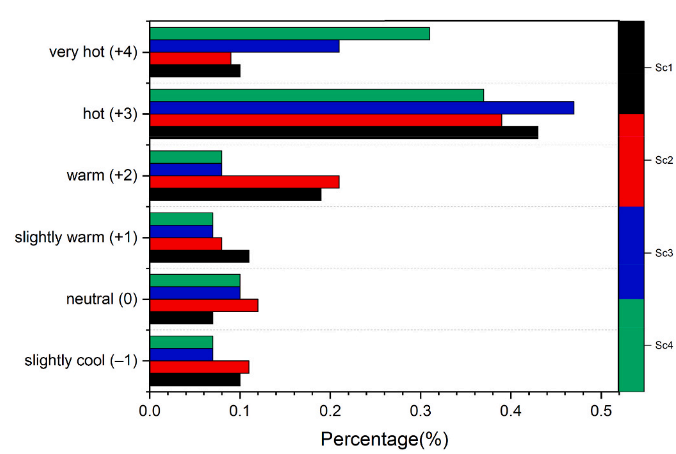

Fig. 7. Percentage of scale voted in various scenarios.

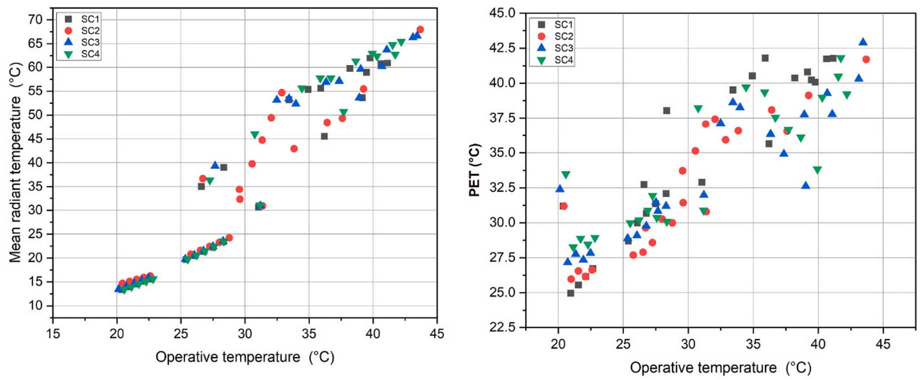

Fig. 8. The relationship between mean radiant temperature and PET with operative temperature in whole scenarios.

conditions reported in SC2, all locations experienced significant heat exposure during the study period.

3.4. Outdoor thermal comfort index (PET) versus thermal sensation

The study employed Rayman to calculate the PET, using Ta, Rh, Ws, and a simulated Tmrt. To obtain the MRT, the researchers utilized Eq (3). The participants' age, activity levels, and heights were also recorded and incorporated into the computation of the PET index. Additionally, the researchers noted that the degree of acclimatization to local conditions is influenced by prior exposure and may significantly impact an individual's perception of the thermal environment. It is crucial to consider the adaptive response of individuals to specific thermal conditions in evaluating their thermal comfort. To establish the correlation between PET and TSV, the initial step involves computing the mean thermal sensation votes (MTSV) for every 1 °C PET segment [76]. The present study investigates the relationship between PET and MTSV for each scenario, as represented in Fig. 9. Prior literature, including [59, 72], has established a thermal comfort range of −0.5 to +0.5. In this climate, the study examines four distinct scenarios across 22 districts in Tehran. The results demonstrate that the PET values range from 17.65 °C to 25.74 °C. Notably, Cs4 exhibits the highest PET value (6.89 °C), while SC2 displays the lowest value (4.42 °C). Moreover, cs1 (5.9 °C) and cs3 (6.44 °C) are in the next positions.

3.4.1. PMV and thermal sensation

Fig. 10 presents a graphical representation of the correlations between Predicted Mean Vote (PMV), Mean Thermal Sensation Vote (MTSV), and Operative Temperature (T_{op}). Consistent with previous research (ANSI/ASHRAE. Standard 5 (2017)), a robust linear relationship was observed between PMV and T_{op} across all scenarios. According to Fanger's recommendations for indoor thermal environments [73], the PMV should satisfy specific conditions, including a range between −2 and +2 and a maximum air temperature (Ta) of 30 °C. Based on the results shown in Fig. 10, it was evident that the PMV performed adequately when T_{op} was below 30.8 °C, 30.93 °C, 30.73 °C, and 30.5 °C, respectively, for each scenario. As the T_{op} temperature rose in outdoor environments with high Ta levels, the contrast between the PMV and MTSV grew more distinct, and the impact of T_{op} on MTSV became apparent. While the connection between T_{op} and MTSV was unclear. It's worth noting that when Top was less than 34 °C, MTSV rose as T_{op} increased. On the other hand, when T_{op} surpassed 34 °C, the PMV overestimated thermal sensations because it didn't account for human thermal adaptation in hot environments. It has been observed that in real-world outdoor thermal conditions [77],individuals adapt their thermal experience through diverse strategies, encompassing physiological, psychological, and behavioral adjustments. Individuals actively engage with their environment to improve their surroundings. The majority of participants reported feeling significant heat when the operative temperature surpassed 30 °C. Thus, evaluating outdoor thermal environments above 30 °C using PMV may require modification. In this regard and based on the analysis and findings, it can be concluded that Sc2 and Sc4 represent the most and least comfortable thermal conditions, respectively.

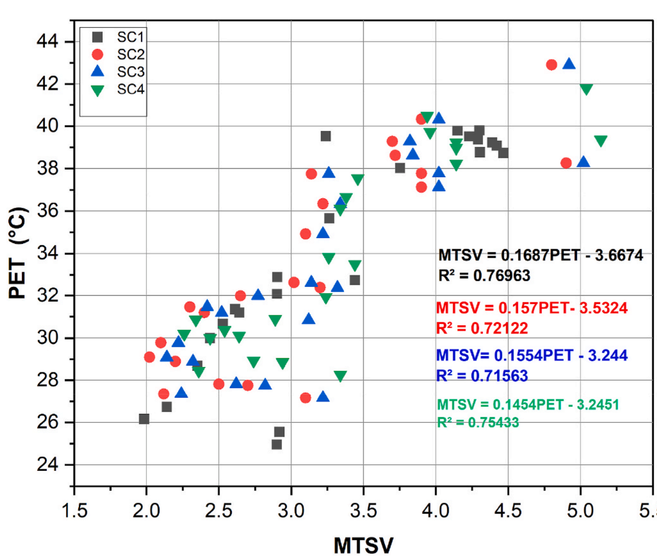

Fig. 9. MTSV versus PET comfort index in whole scenarios.

4. Discussion

4.1. Scale for voting on thermal sensation

Assessing subjective thermal sensations is commonly regarded as an essential aspect, highlighting the significance of implementing a suitable thermal sensation rating scale. Previous investigations have indicated that the most widely utilized scale is the ASHRAE 7-point scale, which includes subdivisions ranging from −3 (cold) to 3 (hot) ((ANSI/ASHRAE. Standard 5 (2017)). The assessment of indoor thermal conditions in accordance with ANSI/ASHRAE Standard 5 (2017) and ISO (7730) (2005) [78] involved the use of a 7-point rating scale. Regarding our assessments, the indoor air temperature was trying to be maintained within certain limits. An instance of this could be seen in the ISO (7730) (2005) guidelines that dictate the acceptable indoor temperature (Ta) to be maintained between 10 and 30 °C and the mean radiant temperature (Tmrt) to be within 10–40 °C [45]. Nonetheless, the ASHRAE Standard has based its comfort standards on past experiments conducted in climate chambers, which revealed that the air temperature rated as comfortable for all participants ranged from 16.7 °C to 36.6 °C [79]. Thus, the 7-point scale was utilized to assess the thermal conditions in

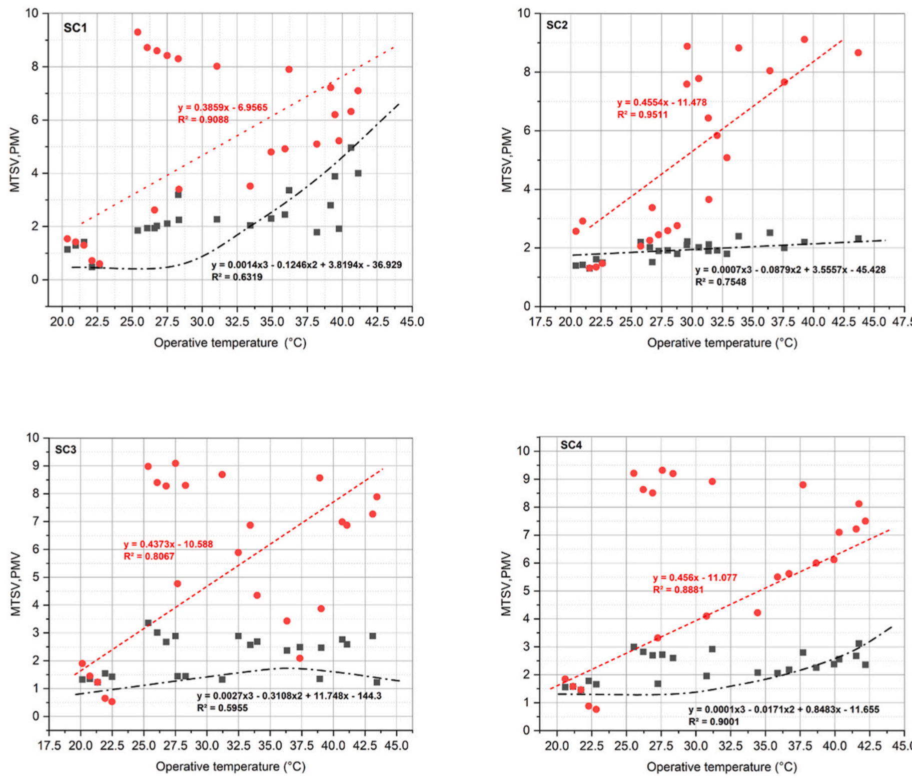

Fig. 10. Difference between PMV (red) and MTSV (black) respectively versus operative temperature in whole scenarios. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

situations where Ta (ambient temperature) was nearing or exceeding the maximum threshold of indoor thermal comfort. [80] An experimental study [78] was conducted, which revealed that at a temperature of 34.0 °C, a considerable proportion of the body exhibited sweating accompanied by a sensation of warmth. The investigation was performed in an environmental enclosure that sustained a relative humidity level of 65% and an airflow rate of 0.15 m/s. The study participants reported a maximum warmth sensation of 3.1 and a maximum dampness sensation of 2.4, which is considered quite high. Although personal cooling systems can help maintain thermal comfort in warm indoor settings without HVAC when temperatures are below 32.0 °C [81], it becomes challenging to keep the human body in the thermal comfort zone when personal cooling systems are used in hot indoor environments where temperatures exceed 34.0 °C [82]. Thus, the 7-point scale provides a suitable means of evaluating both indoor and outdoor thermal environments [46,83].

Table 4 depicts that all surveys were conducted during hot summers. The studies of outdoor thermal environments in cities with cold semi-arid climates has revealed that temperatures can rise above 45 °C, and Tmrt (mean radiant temperature) can exceed 78 °C due to intense solar radiation. This investigation primarily aims to examine the influence of environmental factors on outdoor thermal comfort. As a result, the subjects likely experienced extreme or very hot thermal sensations, rendering the 7-point scale inadequate to evaluate their thermal perception. To account for the greater variability in outdoor climates, some studies utilized a 9-point scale, an extension of the ASHRAE 7-point scale, to assess outdoor thermal sensations.

This table presents six such research conducted in a cold and dry, hot-arid, semi-arid, and cool desert climate. Fig. 10 indicates that the MTSV exceeded 3.1 when T_{op} went beyond 34 °C. In this survey, it would be more reasonable to utilize the 9-point thermal sensation vote scale for evaluating the outdoor thermal environment. study carried out in Tehran, a city with a dry climate, showed that the temperature variations throughout the year have led to an unacceptable level of heat during the summer season. The majority of participants (ranging from 69% to 76% in different scenarios) expressed a preference for TSVs that are categorized as 'warm' to 'very hot', with 'hot' being the most popular option. The central TSV categories, including 'slightly warm', 'neutral', and 'slightly cool', received very few votes, ranging from 0.24% to 0.31% in each scenario. Sc2, Sc3, and Sc4 had a greater number of 'neutral' votes, which suggests that finding comfortable thermal conditions during the summer was infrequent. The average temperature, mean radiant

Table 4
Thermal sensation scale employed in surveys.

Location	Climate characters	Thermal sensation scale	Domain of T_a(°C)	Domain of T_{mrt} (°C)	Authors
Isfahan	dry and low rainfall climate	ASHRAE 9-point	25.4–33.7	19.4–58.3	[59]
Damascus	cool desert climate	ASHRAE 9-point	17.3–38.3	27.4–71.4	[84]
Tabriz	cold and dry climate	ASHRAE 9-point	16.5–28.5	17.7–55.6	[42]
Tehran	cold semi-arid climate	ASHRAE 7-point	22.8–37.5	20.1–49.1	[66]
Tempe	semi-arid climate	ASHRAE 9-point	26.3–38.5	25.4–52.2	[85]
Birjand	hot-arid climate	ASHRAE 7-point	23.2–26.2	36–69.3	[86]
Mendoza	hot-arid climate	ASHRAE 9-point	17.3–39.6	27.4–61.2	[65]
Ahvaz	hot arid desert	ASHRAE 7-point	34–45	31–78	[87]
Be'er Sheva	hot arid climate	ASHRAE 9-point	19.3–33.3	16.3–54.1	[88]
Cairo	hot arid climate	ASHRAE 7-point	26.8–37.5	23.4–62.1	[89]
Konya	cold semi-arid climate	ASHRAE 7-point	27.3–31.5	20.4–47.8	[90]

temperature, and air velocity in these scenarios were approximately between 27.69 and 28.12 °C, 33.77–38.92 °C, and 1.5–3.1 ms−1. The present discovery aligns with the investigation carried out by Refs. [66, 70]in cities with hot-summer weather like Changsha and Teheran, where the annual fluctuation in average air temperature was recorded at 21.6 °C and 24.3 °C, respectively. Conversely, in cities with lower annual fluctuations of mean air temperature (below 20 °C), such as Tianjin or Athens, people may be more adapted to either warm or cool conditions. Research by Refs. [55,91] has reinforced this observation, indicating significant levels of TSV = 0 votes during the colder months in such weather conditions.

The findings of the statistical analysis using linear regression to investigate the relationship between thermal indices and subjective thermal sensation votes (TSV) suggest that the strength of the correlation between TSV and indices was more pronounced during the summer season. Specifically, the coefficient of determination for PET was 0.76 (sc1), 0.72(sc2), 0.71(sc3), and 0.75(sc4), whereas, for PMV, it was 0.81 (sc1), 0.74(sc2), 0.84(sc3), and 0.71(sc4) (refer to Figs. 9 and 10 for a graphical representation). This finding is consistent with previous research conducted by Mohammad and Mohammadzadeh in Roorkee and Tabriz, where they reported a significant correlation between actual TSV and PET during hot weather conditions and a more accurate prediction of outdoor thermal sensation in such climates [42,52]. The results of the current study support earlier findings regarding the relationship between the PMV and TSV,Where [55,67], observed that PMV tended to overestimate TSV in the hotter end of the spectrum during summer in locations with Cwa and Dwa climates such as Hong Kong and Tianjin.

4.2. Disparities in existing thermal indices

The T_{op} index is commonly used to evaluate the indoor thermal environment and is defined in ANSI/ASHRAE Standard 5 (2017) [78]. It is calculated by averaging the air temperature (Ta) and mean radiant temperature (Tmrt) and adjusting them based on the convective heat transfer coefficient and linearized radiant heat transfer coefficient for the occupant. ISO (7730) (2005) [45]and GB/T(5078)5-(2012) (2012) GB/T50785-, 2012 GB/T(5078)5-(2012) (2012) [92] are other standards that use Top. Recent studies have found a strong linear correlation between Top and thermal sensation within the range of 22–30 °C, such as the study by Ref. [46]. In addition [93], discovered that MTSV can be predicted by Top using a linear model in the context of thermal comfort evaluation in urban green spaces on a Dutch university campus. The findings of the study revealed that a linear model can be used to forecast the MTSV using the Top parameter. Fig. 10 illustrates that Top has a strong linear correlation with various thermal comfort indices, with most of the average R2 values being between 0.61 and 0.9. This suggests that Top can be utilized in assessing outdoor thermal conditions. To compare heat stress levels across different thermal comfort indices (PET, MRT), the Top values for each heat stress category were determined using the linear regression equations presented in Fig. 8.

After conducting numerous surveys, Table 5 displays the Top limits of heat stress categories PET index. The Top range of “Strong heat stress” in Taiwan [94], Guangzhou [46], and the EU [95,96] are respectively 35.2–38.6 °C, >34.0 °C and 32.7–37.8 °C. On the other hand, the ranges between 31.84 and 35.2 °C in Taiwan, 30.0–34.0 °C in Guangzhou and, 27.6–32.7 for the EU were regarded as “Moderate heat stress”. Moreover, the range between 28.5 and 31.8 °C, 28–30 °C, and 22.6–27.6 °C are recorded in Taiwan, Guangzhou, and EU respectively as “slightly warm”. Based on the results depicted in Fig. 10, it can be concluded that a thermal sensation of “hot” is experienced when the operative temperature exceeds 32 °C. The temperature range between 30 and 34.0 °C is considered “warm”, and the range of 28–30 °C is regarded as “slightly warm”. The findings of this study align with EU research; however, there were slight variations compared to studies conducted in Taiwan and Guangzhou. One possible explanation for this discrepancy could be the different climatic conditions between these locations and the setting of the current study. Moreover, there is a likelihood that the outcomes might have been impacted by comparable social, economic, and cultural aspects, along with psychological adjustments, in Taichung city and Guangzhou, albeit composed of different terminologies.

It is also worth mentioning, the research conducted on the microenvironment of several open-air settings in Tehran, Iran, has several limitations that need to be considered. The study was limited to a specific location, and the findings may not be generalizable to other regions or cities with different climatic conditions. Furthermore, the research was conducted during a 16-day period in the summer season, which may not be applicable to other seasons or times of the year. The study also simplified certain complex factors that influence outdoor thermal satisfaction, and the findings may not provide a comprehensive understanding of the intricacies involved. Additionally, the study only focuses on three major thermal comfort indices, and other factors such as Universal Thermal Climate (UTCI) have not been considered. Therefore, these limitations should be considered when interpreting the results of this study. On the other hand, in forthcoming studies, it would be prudent to delve into the influence of diverse parameters on outdoor thermal comfort in distinct seasons, such as clothing insulation and metabolic rates, among other factors. This approach would lead to a more comprehensive understanding of the complex nature of this phenomenon.

5. Conclusions

The objective of this research is to examine the microenvironment of several open-air settings situated in Tehran, Iran. The location in question is recognized for its dry and barren weather pattern, including chilly winters, identified as BWh. The investigation focuses on exploring the relationship between three major thermal comfort indices, namely Predicted Mean Vote (PMV), Physiological Equivalent Temperature (PET), and actual thermal sensation votes (TSV) provided by individuals. The research was conducted in district 22 during a 16-day period, from 12th to 27th July 2019, utilizing both microclimatic measurements and questionnaire surveys. The analysis of 680 questionnaires provided valuable insights into the following outcomes:

By examining different measures of thermal comfort alongside the Top index, significant linear connections were found among Top and

Table 5
Heat stress categories

PET [46,94–96]						Recent research
Thermal sensation	EU	Taiwan	T_{op}(EU)	T_{op}(Taiwan)	T_{op}(Guangzhou)	T_{op}
Extreme heat stress	>41	>42	>37.8	>38.6	–	–
Strong heat stress	35–41	38–42	32.7–37.8	35.2–38.6	>34.0	>33.2
Moderate heat stress	29–35	34–38	27.6–32.7	31.8–35.2	30.0–34.0	28.3–33.2
Slight heat stress	23–29	30–34	22.6–27.6	28.5–31.8	28–30	23.4–28.3
No thermal stress	18–23	26–30	18.4–22.6	25.1–28.5	–	–
Slight cold stress	13–18	22–26	14.1–18.3	21.7–25.1	–	–
Moderate cold stress	8–13	18–22	9.9–14.1	18.3–21.7	–	–
Strong cold stress	4–8	14–18	6.5–9.9	15.0–18.3	–	–

PET, Tmrt, and PMV across all situations, with correlation coefficients near 0.9.

The results recorded that Sc2 and Sc4 represented the most and least comfortable thermal conditions, respectively.

The study also found that the PMV performed adequately when Top was below 30.8 °C–30.93 °C, 30.73 °C, and 30.5 °C for each scenario. However, when Top surpassed 34 °C, the PMV overestimated thermal sensations because it didn't account for human thermal adaptation in hot environments. The study concluded that evaluating outdoor thermal environments above 30 °C using PMV may require modification.

The correlation among various thermal comfort indicators and the MTSV in high-temperature outdoor settings was also examined. It was recommended that using non-linear regression formulas could be more appropriate in anticipating thermal comfort during excessively hot circumstances.

Furthermore, this study emphasizes notable distinctions between the primary heat stress classifications and the ones established in this research, suggesting the necessity of revising heat stress classifications to assess outdoor thermal conditions in Tehran. Nonetheless, it should be acknowledged that outdoor thermal satisfaction is affected by various intricate factors, surpassing those encountered indoors. Since this study is validation research, certain realistic limiting factors were suitably simplified.

Architects generally can determine the optimal placement of buildings to establish a self-structuring block oriented in a north-south direction (SC2). Once the best placement method is identified, architects can utilize the research results to select the ideal building height that minimizes thermal islands in their designs.

CRediT authorship contribution statement

Alireza Karimi: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Atousa Bayat:** Writing – original draft, Visualization. **Negar Mohammadzadeh:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Mostafa Mohajerani:** Writing – original draft, Methodology, Investigation, Data curation. **Mansour Yeganeh:** Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

[1] B. Mahdavi Estalkhsari, P. Mohammad, A. Karimi, Land use and land cover change dynamics and modeling future urban growth using cellular automata model over isfahan metropolitan area of Iran, in: Ecological Footprints of Climate Change, Springer, 2022, pp. 495–516.

[2] A. Karimi, et al., Surface urban heat island assessment of a cold desert city: a case study over the isfahan metropolitan area of Iran, Atmosphere (Basel). 12 (10) (2021) 1368.

[3] B. Mahdavi, E. Pir, M. Niloofar, Change detection in a rural landscape : a case study of processes and main driving factors along with its response to thermal environment in Farim , Iran, Environ. Sci. Pollut. Res., no. Pineda (2000) 2022, https://doi.org/10.1007/s11356-022-24504-5.

[4] A. Karimi, P. Mohammad, A. García-Martínez, D. Moreno-Rangel, D. Gachkar, S. Gachkar, New developments and future challenges in reducing and controlling heat island effect in urban areas, Environ. Dev. Sustain. (2022) 1–47.

[5] S. Ahmadi, M. Yeganeh, M.B. Motie, A. Gilandoust, The role of neighborhood morphology in enhancing thermal comfort and resident's satisfaction, Energy Rep. 8 (2022) 9046–9056.

[6] Y. Zhou, N. An, J. Yao, Characteristics, progress and trends of urban microclimate research: a systematic literature review and bibliometric analysis, Buildings 12 (7) (2022) 877.

[7] N. Nazarian, et al., Integrated assessment of urban overheating impacts on human life, Earth's Future 10 (8) (2022), e2022EF002682.

[8] A. Karimi, H. Sanaieian, H. Farhadi, S. Norouzian-Maleki, Evaluation of the thermal indices and thermal comfort improvement by different vegetation species and materials in a medium-sized urban park, Energy Rep. 6 (2020) 1670–1684.

[9] C. Engineers, Handbook–Fundamentals, 1985, pp. 1–24. Atlanta, GA ASHRAE.

[10] S. Teshnehdel, H. Akbari, E. Di Giuseppe, R.D. Brown, Effect of tree cover and tree species on microclimate and pedestrian comfort in a residential district in Iran, Build. Environ. 178 (2020), https://doi.org/10.1016/j.buildenv.2020.106899. May.

[11] J. Spagnolo, R. De Dear, A field study of thermal comfort in outdoor and semi-outdoor environments in subtropical Sydney Australia, Build. Environ. 38 (5) (2003) 721–738.

[12] N. Falah, A. Karimi, A.T. Harandi, Urban growth modeling using cellular automata model and AHP (case study: Qazvin city), Model. Earth Syst. Environ. 6 (1) (2020), https://doi.org/10.1007/s40808-019-00674-z.

[13] S.Y. Chan, C.K. Chau, T.M. Leung, On the study of thermal comfort and perceptions of environmental features in urban parks: a structural equation modeling approach, Build. Environ. 122 (2017) 171–183, https://doi.org/10.1016/j.buildenv.2017.06.014.

[14] H. Swaid, M. Bar-El, M.E. Hoffman, A bioclimatic design methodology for urban outdoor spaces, Theor. Appl. Climatol. 48 (1993) 49–61.

[15] A. Karimi, P. Mohammad, Effect of outdoor thermal comfort condition on visit of tourists in historical urban plazas of Sevilla and Madrid, Environ. Sci. Pollut. Res. (2022) 1–21.

[16] A. Karimi, et al., Assessment of outdoor design conditions on the energy performance of cooling systems in future climate scenarios—a case study over three cities of Texas, Unites States, Sustainability 14 (22) (2022), 14848.

[17] M.M.E. Van Esch, R.H.J. Looman, G.J. de Bruin-Hordijk, The effects of urban and building design parameters on solar access to the urban canyon and the potential for direct passive solar heating strategies, Energy Build. 47 (2012) 189–200.

[18] R. Zhu, et al., Effects of district parameters, green space and building density on thermal comfort-a case study of Badaguan District in Qingdao, Case Stud. Therm. Eng. 42 (2023), 102705.

[19] K. Wong, E. Ng, R. Yau, Urban ventilation as a countermeasure for heat islands toward quality and sustainable city planning in Hong Kong, J. Heat Isl. Inst. Int. 7 (2) (2012) 11–17.

[20] K.-M. Wai, C. Yuan, A. Lai, K.N. Peter, Relationship between pedestrian-level outdoor thermal comfort and building morphology in a high-density city, Sci. Total Environ. 708 (2020), 134516.

[21] Z. Zare, M. Yeganeh, N. Dehghan, Environmental and social sustainability automated evaluation of plazas based on 3D visibility measurements, Energy Rep. (2022).

[22] F. Ali-Toudert, H. Mayer, Effects of asymmetry, galleries, overhanging facades and vegetation on thermal comfort in urban street canyons, Sol. Energy 81 (6) (2007) 742–754.

[23] F. Ali-Toudert, H. Mayer, Numerical study on the effects of aspect ratio and orientation of an urban street canyon on outdoor thermal comfort in hot and dry climate, Build. Environ. 41 (2) (2006) 94–108.

[24] W. Yang, N.H. Wong, S.K. Jusuf, Thermal comfort in outdoor urban spaces in Singapore, Build. Environ. 59 (2013) 426–435.

[25] M. Karimimoshaver, M.S. Shahrak, The effect of height and orientation of buildings on thermal comfort, Sustain. Cities Soc. 79 (2022), 103720.

[26] M. Afsharzadeh, M. Khorasanizadeh, S. Norouzian-Maleki, A. Karimi, Identifying and prioritizing the design attributes to improve the use of besat park of Tehran, Iran, Iran Univ. Sci. Technol. 31 (3) (2021) 1–24.

[27] S. Mohammad, A. Shea, Performance evaluation of modern building thermal envelope designs in the semi-arid continental climate of Tehran, Buildings 3 (4) (2013) 674–688.

[28] S. Zafarmandi, M. Mahdavinejad, L. Norford, A. Matzarakis, Analyzing thermal comfort sensations in semi-outdoor space on a university campus: on-site measurements in Tehran's hot and cold seasons, Atmosphere (Basel). 13 (7) (2022) 1034.

[29] R. Doostan, B. Alijani, Evaluating the onset, end, and length of seasons in selected stations in Iran, Theor. Appl. Climatol. (2022) 1–16.

[30] S. Amindeldar, S. Heidari, M. Khalili, The effect of personal and microclimatic variables on outdoor thermal comfort: a field study in Tehran in cold season, Sustain. Cities Soc. 32 (2017) 153–159.

[31] M. Bokaie, M.K. Zarkesh, P.D. Arasteh, A. Hosseini, Assessment of urban heat island based on the relationship between land surface temperature and land use/ land cover in Tehran, Sustain. Cities Soc. 23 (2016) 94–104.

[32] S.N. Kandelan, M. Yeganeh, S. Peyman, K. Panchabikesan, U. Eicker, Environmental study on freenery planning scenarios to improve the air quality in urban canyons, Sustain. City Soc. (2022), 103993.

[33] S. Alijani, A. Pourahmad, H.H. Nejad, K. Ziari, S. Sodoudi, A new approach of urban livability in Tehran: thermal comfort as a primitive indicator. Case study, district 22, Urban Clim. 33 (2020), 100656.

[34] M. Kasmaei, Architecture and Climate, kaktus publisher, Tehran, 1995.
[35] M. Falahati, L. Akhlaghi, A.R. Lari, R. Alaghehbandan, Epidemiology of dermatophytoses in an area south of Tehran, Iran, Mycopathologia 156 (2003) 279–287.
[36] F. Mostafavi, M. Tahsildoost, Z. Zomorodian, Energy efficiency and carbon emission in high-rise buildings: a review (2005-2020), Build. Environ. 206 (2021), 108329.
[37] A. Wood, S. Henry, Best Tall Buildings: CTBUH Awards: A Global Overview of 2016 Skyscrapers, 2016.
[38] R.M. Foster, M.H. Ramage, T. Reynolds, Rethinking CTBUH height criteria in the context of tall timber, CTBUH J 4 (2017) 28–33.
[39] H. Farhadi, M. Faizi, H. Sanaieian, Mitigating the urban heat island in a residential area in Tehran: investigating the role of vegetation, materials, and orientation of buildings, Sustain. Cities Soc. 46 (2019), 101448, https://doi.org/10.1016/j.scs.2019.101448. June 2018.
[40] R.A. García-Ruiz, J. López-Martínez, J.L. Blanco-Claraco, J. Pérez-Alonso, Á. J. Callejón-Ferre, On air temperature distribution and ISO 7726-defined heterogeneity inside a typical greenhouse in Almería, Comput. Electron. Agric. 151 (2018) 264–275.
[41] Z. Li, Q. Zhang, G. Zhang, G. Song, F. Fan, Insight of environmental quality of a semi-enclosed large-scale stadium during football matches: a case study in Harbin, China, Build. Environ. 217 (2022), 109103.
[42] N.M. Zadeh, A. Karimi, R.D. Brown, The influence of outdoor thermal comfort on acoustic comfort of urban parks based on plant communities, Build. Environ. (2022), 109884.
[43] Z. Fang, X. Feng, Z. Lin, Investigation of PMV model for evaluation of the outdoor thermal comfort, Procedia Eng. 205 (2017) 2457–2462.
[44] G. Havenith, et al., A database of static clothing thermal insulation and vapor permeability values of non-Western ensembles for use in ASHRAE Standard 55, ISO 7730, and ISO 9920, Ashrae Trans 121 (1) (2015) 197–215.
[45] A. Ac08024865, Ergonomics of the Thermal Environment-Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria, ISO, 2005.
[46] Z. Fang, et al., Investigation into the differences among several outdoor thermal comfort indices against field survey in subtropics, Sustain. Cities Soc. 44 (2019) 676–690.
[47] C.A. Vargas Salgado, C.D. Chiñas Palacios, J. Águila León, D. Alfonso, Solar, "Measurement of the black globe temperature to estimate the MRT and WBGT indices using a smaller diameter globe than a standardized one: experimental analysis,", in: Proceedings 5th CARPE Conference: Horizon Europe and beyond, Editorial Universitat Politècnica de València, 2019, pp. 201–207.
[48] B.W. Olesen, R. Nielsen, Thermal insulation of clothing measured on a movable thermal manikin and on human subjects, ECSC Program. Res. (1983) 914, 7206/00.
[49] E.A. McCullough, B.W. Jones, J. Huck, A comprehensive data base for estimating clothing insulation, Ashrae Trans 91 (2) (1985) 29–47.
[50] Y. Nishi, G. Rr, G. Ap, DIRECT MEASUREMENT OF CLOTHING HEAT TRANSFER PROPERTIES DURING SENSIBLE AND INSENSIBLE HEAT EXCHANGE WITH THERMAL ENVIRONMENT, 1975.
[51] R. Nielsen, B.W. Olesen, P.O. Fanger, Effect of physical activity and air velocity on the thermal insulation of clothing, Ergonomics 28 (12) (1985) 1617–1631.
[52] P. Mohammad, S. Aghlmand, A. Fadaei, S. Gachkar, D. Gachkar, A. Karimi, Evaluating the role of the albedo of material and vegetation scenarios along the urban street canyon for improving pedestrian thermal comfort outdoors, Urban Clim. 40 (2021), 100993, https://doi.org/10.1016/j.uclim.2021.100993.
[53] O. internationale, de normalisation, *Moderate Thermal Environments: Determination of the PMV and PPD indices and specification of the conditions for thermal comfort*, International Organization for Standardization, 1994.
[54] A. Yaacoub, M. Esseghir, L. Merghem-Boulahia, A review of different methodologies to study occupant comfort and energy consumption, Energies 16 (4) (2023) 1634.
[55] D. Lai, D. Guo, Y. Hou, C. Lin, Q. Chen, Studies of outdoor thermal comfort in northern China, Build. Environ. 77 (2014) 110–118.
[56] I. Hussein, M.H.A. Rahman, Field Study on Thermal Comfort in Malaysia, 2009.
[57] K. Blazejczyk, Y. Epstein, G. Jendritzky, H. Staiger, B. Tinz, Comparison of UTCI to selected thermal indices, Int. J. Biometeorol. 56 (2012) 515–535.
[58] X. Tian, Z. Lin, Predicting personalized thermal comfort in stratified micro-environments using turbulent jet theories and data-driven models, Build. Environ. 110009 (2023).
[59] N. Narimani, A. Karimi, R.D. Brown, Effects of street orientation and tree species thermal comfort within urban canyons in a hot, dry climate, Ecol. Inf. (2022), 101671.
[60] P. Höppe, Die energiebilanz des menschen, vol. 49, Univ., Meteorolog. Inst., 1984.
[61] P. Höppe, The physiological equivalent temperature - a universal index for the biometeorological assessment of the thermal environment, Int. J. Biometeorol. 43 (2) (1999) 71–75, https://doi.org/10.1007/s004840050118.
[62] B. Givoni, et al., Outdoor comfort research issues, Energy Build. 35 (1) (2003) 77–86.
[63] N. Metje, M. Sterling, C.J. Baker, Pedestrian comfort using clothing values and body temperatures, J. Wind Eng. Ind. Aerod. 96 (4) (2008) 412–435.
[64] L. Monteiro, Thermal Comfort Predictive Models: Quantification of Relationships between Microclimatic and Thermal Sensation Variables for Outdoor Spaces Assessment and Design, 2008.
[65] M.A. Ruiz, E.N. Correa, Adaptive model for outdoor thermal comfort assessment in an Oasis city of arid climate, Build. Environ. 85 (2015) 40–51.
[66] M. Hadianpour, M. Mahdavinejad, M. Bemanian, F. Nasrollahi, Seasonal Differences of Subjective Thermal Sensation and Neutral Temperature in an Outdoor Shaded Space in Tehran, Iran, vol. 39, Sustain. cities Soc., 2018, pp. 751–764.
[67] V. Cheng, E. Ng, C. Chan, B. Givoni, Outdoor thermal comfort study in a sub-tropical climate: a longitudinal study based in Hong Kong, Int. J. Biometeorol. 56 (2012) 43–56.
[68] S. Coccolo, J. Kämpf, J.-L. Scartezzini, D. Pearlmutter, Outdoor human comfort and thermal stress: a comprehensive review on models and standards, Urban Clim. 18 (2016) 33–57.
[69] M. Nikolopoulou, Designing Open Spaces in the Urban Environment: a Bioclimatic Approach, Centre for Renewable Energy Sources, EESD, FP5, 2004.
[70] W. Liu, Y. Zhang, Q. Deng, The effects of urban microclimate on outdoor thermal sensation and neutral temperature in hot-summer and cold-winter climate, Energy Build. 128 (2016) 190–197.
[71] A. Alahmer, M.A. Omar, A. Mayyas, S. Dongri, Effect of relative humidity and temperature control on in-cabin thermal comfort state: Thermodynamic and psychometric analyses, Appl. Therm. Eng. 31 (14–15) (2011) 2636–2644.
[72] R. Mora, R. Bean, Thermal comfort: designing for people, ASHRAE J. 60 (2) (2018) 40–46.
[73] P.O. Fanger, Thermal comfort. Analysis and applications in environmental engineering, Therm. Comf. Anal. Appl. Environ. Eng. (1970).
[74] K. Pantavou, G. Theoharatos, M. Santamouris, D. Asimakopoulos, Outdoor thermal sensation of pedestrians in a Mediterranean climate and a comparison with UTCI, Build. Environ. 66 (2013) 82–95.
[75] ASHRAE, "ASHRAE Standard 169—Climatic Data for Building Design Standards, American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2013.
[76] R.J. De Dear, G.S. Brager, Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55, Energy Build. 34 (6) (2002) 549–561.
[77] J.F. Nicol, M.A. Humphreys, Adaptive thermal comfort and sustainable thermal standards for buildings, Energy Build. 34 (6) (2002) 563–572.
[78] A.N.S. Institute, Thermal Environmental Conditions for Human Occupancy, vol. 55, American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2004, 2004.
[79] K. Parsons, Human Thermal Environments: the Effects of Hot, Moderate, and Cold Environments on Human Health, Comfort, and Performance, CRC press, 2014.
[80] W. Song, F. Wang, F. Wei, Hybrid cooling clothing to improve thermal comfort of office workers in a hot indoor environment, Build. Environ. 100 (2016) 92–101.
[81] D.G. Scheatzle, H. Wu, J. Yellott, Extending the summer comfort envelope with ceiling fans in hot, arid climates, Build. Eng. 95 (1989) 269–280.
[82] L. Huang, Q. Ouyang, Y. Zhu, L. Jiang, A study about the demand for air movement in warm environment, Build. Environ. 61 (2013) 27–33.
[83] C. Deb, A. Ramachandraiah, Evaluation of thermal comfort in a rail terminal location in India, Build. Environ. 45 (11) (2010) 2571–2580.
[84] M.W. Yahia, E. Johansson, Evaluating the behaviour of different thermal indices by investigating various outdoor urban environments in the hot dry city of Damascus, Syria, Int. J. Biometeorol. 57 (2013) 615–630.
[85] A. Middel, N. Selover, B. Hagen, N. Chhetri, Impact of shade on outdoor thermal comfort—a seasonal field study in Tempe, Arizona, Int. J. Biometeorol. 60 (2016) 1849–1861.
[86] S. Khalili, R. Fayaz, S.A. Zolfaghari, Analyzing Outdoor Thermal Comfort Conditions in a University Campus in Hot-Arid Climate: A Case Study in Birjand, Iran, vol. 43, Urban Clim., 2022, 101128.
[87] N. Nasrollahi, Y. Namazi, M. Taleghani, The effect of urban shading and canyon geometry on outdoor thermal comfort in hot climates: a case study of Ahvaz, Iran, Sustain. Cities Soc. 65 (2021), 102638.
[88] P. Cohen, et al., Urban outdoor thermal perception in hot arid Beer Sheva, Israel: methodological and gender aspects, Build. Environ. 160 (2019), 106169.
[89] M.H. Elnabawi, N. Hamza, S. Dudek, Thermal perception of outdoor urban spaces in the hot arid region of Cairo, Egypt, Sustain. Cities Soc. 22 (2016) 136–145.
[90] F. Canan, I. Golasi, V. Ciancio, M. Coppi, F. Salata, Outdoor thermal comfort conditions during summer in a cold semi-arid climate. A transversal field survey in Central Anatolia (Turkey), Build. Environ. 148 (2019) 212–224.
[91] A. Tseliou, I.X. Tsiros, M. Nikolopoulou, Seasonal differences in thermal sensation in the outdoor urban environment of Mediterranean climates–the example of Athens, Greece, Int. J. Biometeorol. 61 (2017) 1191–1208.
[92] G. 50785-2012, Evaluation Standard for Indoor Thermal Environment in Civil Buildings, Standardization Administration of China Beijing, 2012.
[93] Y. Wang, R. de Groot, F. Bakker, H. Wörtche, R. Leemans, Thermal comfort in urban green spaces: a survey on a Dutch university campus, Int. J. Biometeorol. 61 (2017) 87–101.
[94] T.-P. Lin, A. Matzarakis, Tourism climate and thermal comfort in sun moon lake, Taiwan, Int. J. Biometeorol. 52 (2008) 281–290.
[95] M. Tsitoura, T. Tsoutsos, T. Daras, Evaluation of comfort conditions in urban open spaces. Application in the island of Crete, Energy Convers. Manag. 86 (2014) 250–258.
[96] A. Matzarakis, H. Mayer, Another Kind of Environmental Stress: Thermal Stress, vol. 18, WHO Newsl., 1996, pp. 7–10. January 1996.