scientific reports

OPEN

Evaluating thermal comfort indices for outdoor spaces on a university campus

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This study evaluates the applicability of three thermal comfort indices—Physiologically Equivalent Temperature (PET), Standard Effective Temperature (SET), and Universal Thermal Climate Index (UTCI)—in various outdoor environments on the campus of Xi'an University, China. Meteorological data were collected on sunny days using a portable weather station at a height of 1.5 m, and subjective questionnaires were administered to 25 healthy university students over three months to gather Thermal Sensation Votes (TSV) and Thermal Comfort Votes (TCV). The study was conducted at four distinct outdoor locations: a lakeside area (Location 1), a shaded path (Location 2), a sports field (Location 3), and a plaza (Location 4). PET, SET, and UTCI values were calculated from the collected data using Rayman software. The analysis revealed significant differences in thermal comfort across the four locations, with the highest proportion of subjects feeling hot at the sports field (54.4%) and the highest proportion feeling cold at the lakeside (39%). The shaded path had the highest proportion of subjects feeling comfortable (79.4%), while the lakeside had the lowest (60.1%). The results indicated that SET underestimated thermal sensation at Locations 1, 3, and 4, necessitating calibration. PET was suitable for Locations 2, 3, and 4 but failed to reflect the thermal sensation at Location 1 due to prolonged sun exposure. In contrast, UTCI demonstrated applicability across all locations. To enhance accuracy, revised indices SET' and PET' were formulated using the mean-median method, providing more precise thermal comfort assessments. These findings underscore the limitations of SET and PET under specific conditions and highlight the robustness of UTCI, offering valuable insights for urban planning and design aimed at improving outdoor thermal comfort and well-being.

Keywords Thermal comfort indices, SET, UTCI, PET, Outdoor spaces

In light of the escalating global warming and rapid urbanization trends, the influence of outdoor thermal comfort on human well-being and satisfaction has become increasingly pronounced[1]. Extended exposure to inhospitable outdoor conditions renders individuals susceptible to various health ailments, including heat stroke, dehydration, and respiratory complications[2]. Consequently, it becomes imperative to comprehensively comprehend the determinants of outdoor thermal comfort and devise efficacious measures to enhance thermal well-being[3].

In recent years, a multitude of scholarly endeavors have been dedicated to investigating the intricacies of outdoor thermal comfort, employing diverse thermal comfort indices, such as the standard effective temperature (SET), universal thermal climate index (UTCI), and physiological equivalent temperature (PET), in appraising distinct outdoor settings[4]. The PET index, developed by Höppe[5], is based on the Munich Individual Energy Balance Model (MEMI). PET is defined as the air temperature at which a standard indoor environment induces the same thermal stress as the actual outdoor conditions being evaluated. Its comprehensiveness—accounting for air temperature, humidity, wind speed, and solar radiation—has led to widespread use in various climate studies. SET, developed by Gagge et al.[6], represents the temperature of a hypothetical environment where the total heat loss from the skin of a person wearing a standard amount of clothing matches the thermal comfort of the actual environment. This index is particularly effective for evaluating thermal comfort in both indoor and outdoor settings[7]. The UTCI, established by the International Society of Biometeorology, provides an internationally recognized standard for evaluating heat stress. It is based on a complex model that incorporates air temperature,

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wind speed, humidity, and radiation[8]. UTCI is acclaimed for its robustness and applicability across diverse climatic conditions, with proven effectiveness in both urban and rural contexts[9,10].

Potchter et al.[4] conducted a comprehensive review of 110 articles focusing on outdoor thermal comfort for the human body. Their findings indicate that researchers from diverse climate zones commonly employ three thermal comfort indices—Physiologically Equivalent Temperature (PET), Universal Thermal Climate Index (UTCI), and Standard Effective Temperature (SET)—for evaluating outdoor thermal comfort. Xu et al.[5] performed an outdoor thermal comfort study in Xi'an, a city situated on the border between semi-arid (BSk) and humid subtropical climates. Their study utilized PET and UTCI to assess the thermal comfort of various urban park landscapes in Xi'an, and they established the ranges for neutral PET and neutral UTCI. Sharmin et al.[6] applied PET to evaluate the current thermal comfort conditions in Dhaka, identifying the acceptable PET range for outdoor individuals, which serves as a reference for tropical climate research. Manob Das et al.[7] employed SET and PET to assess the thermal comfort of urban populations in India. Their findings indicated that PET provides a more accurate reflection of the thermal experience of local residents compared to SET.

Nonetheless, disparities persist in the suitability of these thermal comfort indicators across varying environmental circumstances, particularly in specific geographical locales and diverse outdoor settings[4,11–13]. Matzarakis et al.[13] conducted a comparative study of these indices in a Mediterranean climate, concluding that UTCI most accurately reflects the heat response of the local population. They found that PET and SET require adjustments based on specific local conditions. Similarly, Ali-Toudert and Mayer[14] identified limitations of PET and SET in desert climates, stressing the necessity for their calibration.Consequently, this disparity poses challenges for urban planners and designers in identifying optimal design strategies for outdoor spaces. Hence, a comprehensive comprehension of the determinants influencing outdoor thermal comfort, alongside a nuanced appreciation of the merits and limitations of thermal comfort indices, assumes paramount significance. Moreover, an imperative lies in formulating more efficacious strategies aimed at augmenting outdoor thermal comfort, thereby empowering urban planners and designers to foster enhanced thermal well-being within outdoor environments.

This study systematically evaluated the applicability of three thermal comfort indices—Standard Effective Temperature (SET), Universal Thermal Climate Index (UTCI), and Physiologically Equivalent Temperature (PET)—in four distinct outdoor environments on a university campus in Xi'an, China. Such a multi-scenario comparative study is uncommon in the current body of literature, offering a more holistic understanding of thermal comfort in various outdoor contexts. Furthermore, this paper introduced and validated an innovative thermal comfort index correction method, referred to as the mean-median method. This method calibrates the thermal comfort index, significantly improving its accuracy in specific environments. The proposed method offers new tools for future research to more precisely evaluate outdoor thermal comfort. By identifying the limitations and applicability of various thermal comfort indices in specific environments, this study offers practical guidance for urban planners and designers. This, in turn, can help them better account for thermal comfort when designing outdoor spaces, thereby enhancing human well-being.

Methodology

Study area

Xi'an is located in central China, in the middle of Shaanxi Province, between 105°29'—109°49' east longitude and 33°42'—39°35' north latitude. It is located on the border between semi-arid (BSk) and humid subtropical climate (Cwa). The experimental site is located in a university in Xi'an. The campus covers an area of 961 mu, with green trees, rich landscape and pleasant scenery. It is an ideal research area for conducting campus outdoor thermal comfort research.This locale stands as an optimal setting for conducting outdoor thermal comfort research on campus. Deliberations surrounding the spatial utilization and visible sky factor (SVF) have informed the selection of four representative campus spaces for investigation (Fig. 1). These spaces include East Lake (Place 1), a tree-lined path (Place 2), the campus playground (Place 3), and the campus square (Place 4). By incorporating water features, wooded areas, open squares, and architectural structures, these exemplar spaces collectively encapsulate the distinctive attributes characteristic of various campus locations. A comprehensive overview of the distinguishing traits associated with these four areas is presented in Table 1.

Experimental design

On-site meteorological measurement

To ensure the integrity of the research data and mitigate potential inaccuracies stemming from inclement weather conditions, the collection of on-site meteorological data was confined to sunny days. A portable weather station, placed at an elevation of 1.5 m above ground level, was meticulously positioned by the researchers to facilitate the measurement and recording of meteorological variables, including air temperature (Ta), relative humidity (RH), wind speed (Va), solar radiation (G), and black globe temperature (Tg). The measurement range and precision of the instrumentation employed for data acquisition are expounded in Table 2. Before commencing formal measurements, the portable weather station underwent meticulous calibration by experienced researchers, ensuring data reliability. A data logging frequency of 1 min was configured, with the recorded data automatically uploaded to the meteorological database.

Subjective questionnaire

The questionnaire survey was conducted from May to July 2022 (during the typical summer months in Xi'an), between the hours of 9:00 and 17:00, while simultaneously carrying out on-site meteorological measurements. A total of 1,500 valid questionnaires were collected as the outcome of the study (375 valid questionnaires were collected from each of the four locations).

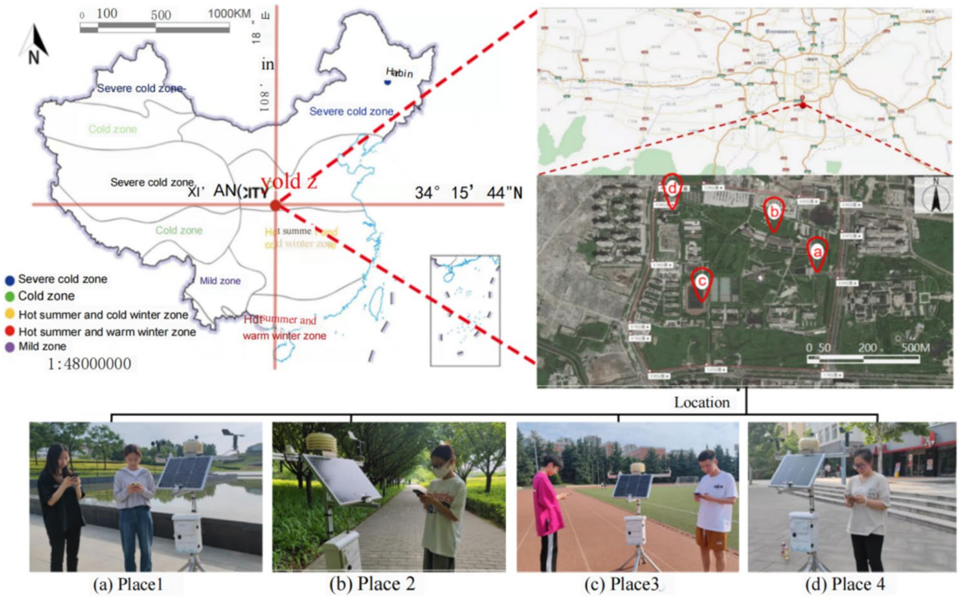


Fig. 1. Study area.

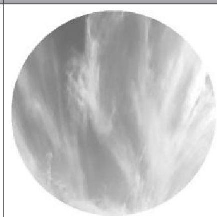
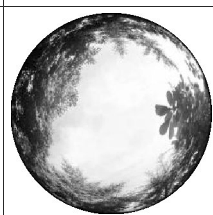
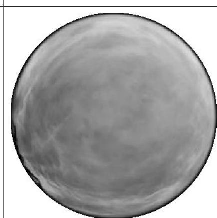
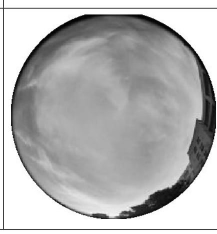
Site	Flooring materials	Place function	Facilities	SVF	
Place 1	Water surface (65%), Square tiles (30%), Concrete (5%)	Gatherings, Socializing	Sinks, Trash cans		SVF = 1.000
Place 2	Tarmac (100%)	Walking, Cycling	Trash cans, Billboards		SVF = 0.452
Place 3	Grass (40%), Plastic track (60%)	Sports, Performances, Rallies	Sports equipment, Streetlights		SVF = 0.989
Place 4	Square brick (80%), Concrete (20%)	Walking, Resting, Exhibition	Billboards, Sunshades, Streetlights		SVF = 0.876

Table 1. Spatial description of the four open spaces.

Instrument	Meteorological parameters	Measuring range	Measuring accuracy
2020 multi-function tester (Air temperature and humidity sensor)	Air temperature	−20–125 ℃	± 0.5 ℃
	Relative humidity	0–100%	± 3%
Delta OHM HD2107.2	Globe temperature	−30–120 ℃	± 0.25 ℃
JT2020 omnidirectional wind speed sensor	Wind speed	0.05–5 m/s	± 0.03 m/s
JT2020 effective temperature sensor	Effective temperature	−20–85 ℃	± 0.5 ℃
SM2026-SOLAR	solar radiation/(W/m^2)	0.1–1999.9 W/m^2	± 10 W/m^2

Table 2. Basic parameters of the measuring instruments used.

This study recruited 25 students as research subjects to conduct a thermal comfort questionnaire survey, including 8 males and 17 females, which is consistent with the male–female ratio of the school. These subjects were divided into five groups, and each group did not interfere with each other during the experiment. The subjects were in good health, had no bad habits, and had lived on campus for at least one year. They had adapted to the local climate and environment and were able to provide objective and accurate feedback. During the study, excluding holidays and special weather conditions, each group completed at least one questionnaire survey every day (i.e., at least 25 questionnaires were collected every day). At the end of the experiment, a total of 1500 valid questionnaires were collected.

Under the guidance of professional researchers, each group visited the designated experimental site for the questionnaire survey. To minimize interference from external factors, subjects were given a 15-min adjustment period upon arrival to stabilize their physiological state. Subsequently, they spent 10 min in the current environment before completing a subjective thermal comfort questionnaire.It took about 25 min for each subject to complete the entire experimental process at one location. At the same time, the meteorological data of the four surveyed locations were recorded using the weather station. The data are shown in Table 3.

The questionnaire comprised two parts. The first part captured basic information about the subjects, such as name, gender, and age. Since this information had already been collected before the start of the experiment, subjects only needed to provide their names while filling out the questionnaire. The second part constituted the core of the questionnaire and included parameters such as clothing thermal resistance coefficient, Thermal Sensation Vote (TSV), Thermal Comfort Vote (TCV), and activity metabolic rate. The metabolic rate was determined based on the subject's activity level in the preceding 15 min. Both thermal sensation voting and thermal comfort voting adhered to a 7-level scale. Thermal sensation votes ranged from -3 (cold) to 3 (hot), while thermal comfort votes ranged from -3 (very uncomfortable) to 3 (very comfortable).The questionnaire details are shown in Fig. 2.

Thermal comfort index

The thermal comfort index serves as a comprehensive measure, encapsulating the combined influence of the prevailing thermal environment and human physiological factors on human thermal comfort. It stands as the foremost metric for evaluating the thermal comfort within a given environment. Since the 1970s, numerous thermal comfort indicators have been proposed, with standard effective temperature (SET), universal thermal climate index (UTCI), and physiological equivalent temperature (PET) emerging as the most widely adopted.

The PET calculation formula is as follows: Formula (1) [5]:

$$R = \left[\frac{r_a(H-E) + 1.2r_s(E-0.1)(5800(1+0.007V)(0.6-f_{cl}) + \theta_{sol}(0.92-0.27f_{cl}) - p_{v,sat}(T_a-2.73)fh_{index} * V)(1-f_w) + 2500f_w}{\rho * c_p * (r_a + r_s)}\right] \tag{1}$$

where, PET is the physiological equivalent temperature, T_a is the air temperature, M is the metabolic rate (in W/m^2), r_a is the convective heat transfer coefficient (in W/(m^2·K)), r_s is the radiation heat transfer coefficient (unit is W/(m^2·K)), H is water evaporation rate (unit is W/m^2), E is water loss rate (unit is W/m^2), V is wind speed, f_{cl} is clothing surface area ratio, θ_{sol} is the solar radiation heat flux, p is the saturated water vapor pressure,fh_{index} is the humidity index, f_w is the humidity of the skin, ρ is the air density, and C_p is the air specific heat capacity.

	Place 1			Place 2			Place 3			Place 4		
Parameters	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean
Ta (℃)	37.5	30.5	35.38	35.5	29.5	32.52	37.5	31.5	34.25	36.5	29.5	33.38
RH (%)	78	57	66.12	66	57	60.55	60	42	50.58	60	45	51.12
Va (m/s)	0.99	0.15	0.78	1.53	0.24	0.93	1.23	0.18	0.81	1.47	0.18	0.87
G (W/m^2)	978	477	657.89	303	68	157.78	780	371	552.53	698	279	495.26
Tg (℃)	39.25	32.5	36.15	36.5	30.25	33.18	39.5	32.5	35.55	38.25	31.5	35.51

Table 3. Environmental parameter table of four test sites.

Questionnaire on outdoor thermal environment quality

Date: **Time:**

Name________

Please describe your current thermal sensation :

Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
-3	-2	-1	0	1	2	3

Please describe your current thermal comfort :

Very discomfort	Discomfort	Slightly discomfort	Neutral	Slightly comfort	Comfort	Very comfort
-3	-2	-1	0	1	2	3

Please describe your current research location:

Place 1	Place 2	Place 3	Place 4
1	2	3	4

Your major activities in past 15 min:

☐Seating ☐Standing ☐Walking ☐Jogging ☐Babysitting ☐Other______________

What are you wearing right now? (If there is no corresponding clothing, please note.)

Upper: Vest、 T-shirt(short sleeves /long sleeves/sleeveless)、 Sweater (short sleeves/long sleeves)、 One-piece dress(thin /thick)、 Jacket or blazer(thin/thick)

Trousers: Dress、 Pants(sweatpants / jeans / informal)、 Length(Ankle-length / Knee-length / shorts)

Socks: Knee socks、Stockings、Ankle-length socks

Shoes:Sandals or flip flops、Boots、Shoes

Overall color: ☐Dark、 ☐Light

Fig. 2. Questionnaire.

The UTCI calculation formula is as follows: Formula (2) [8]:

$$UTCI = T_{amb} + K - (a \times MRT + b \times I_{cl} + c \times f_{cl} \times I_{cl}) \tag{2}$$

where, *UTCI* is the universal thermal comfort index, *Tamb* is the ambient temperature, *K* is the thermal radiation temperature calculated according to the ambient humidity, *MRT* is the average radiation temperature, *Icl* is the thermal resistance coefficient of clothing, *fcl* is the ratio of clothing surface area, *a, b, c* is a series of coefficients, which need to be calculated according to the actual situation.

The SET calculation formula is as follows: Formula (3) [6]:

$$SET = 0.5\left[T_a + T_r + \frac{[(r_{a1} + r_{a2})/2](T_a - T_r)}{r_s + (r_{a1} + r_{a2})/2} + \frac{M}{W}\right] \tag{3}$$

where, *SET* refers to the standard effective temperature, where T_a represents the air temperature, T_r signifies the radiation temperature, r_{a1}, and r_{a2} denote the convective heat transfer coefficients of the two sides of the human body facing the wall within the room, r_s represents the combined radiation heat transfer coefficients of each surface within the room, *M* corresponds to the metabolic rate, and *W* signifies the adiabatic heat of the clothing.

In this study, the Rayman software will be employed to compute the SET, UTCI, and PET indices. The calculation process involves inputting both meteorological data and individual parameter data. The meteorological parameters include air temperature (Ta), relative humidity (RH), wind speed (Va), and solar radiation (G). On the other hand, the individual parameter data encompasses clothing thermal resistance and activity metabolic rate. Through the integration of these data sets, the software facilitates the computation of the desired thermal comfort indices.

Results

Subjective evaluation analysis

Figure 3 depicts the distribution of thermal sensation votes (TSV) among subjects across the four places under investigation.

Among the four places, the "neutral" category (TSV = 0) exhibited the highest percentage distribution among the population (Table 4). Place 1 witnessed approximately 39% of subjects reporting their TSV within the cold range (− 3 to − 1), while 38.1% reported their TSV falling within the hot range (+1 to +3). At Place 2, around 22.3% of subjects registered their TSV in the cold range (− 3 to − 1), whereas a mere 0.419 subjects indicated their TSV within the hot range (+1 to +3). Place 3 showed roughly 18.1% of subjects reporting their TSV in the cold range (− 3 to − 1), while 55.4% reported their TSV within the hot range (+1 to +3). Lastly, Place 4 recorded approximately 16% of subjects reporting their TSV within the cold range (− 3 to − 1), with 52.9% reporting their TSV within the hot range (+1 to +3).

Upon comparing the thermal sensations experienced by subjects across the four places, when sorted by the proportion of individuals feeling hot outdoors (TSV > 0), it became apparent that Place 3 > Place 4 > Place 2 > Place 1. Notably, the proportion of individuals perceiving the environment as hot at Place 3 (54.4%) was 16.3% higher than that observed at Place 1 (38.1%) (Table 4). It means that people feel that Place 3 is hotter outdoors.

Figure 4 illustrates the distribution of thermal comfort votes (TCV) among subjects across the four places under investigation.

At Place 1, approximately 60.1% of subjects expressed TCV within the comfort range (0 to + 3), while 30.9% of subjects reported TCV falling within the uncomfortable range (− 3 to − 1). Conversely, at Place 2, an overwhelming 79.4% of subjects registered TCV within the comfort range (0 to + 3). In Place 3 and Place 4, 65.2% and 65.6% of subjects respectively reported TCV within the satisfactory range, whereas 34.8% and 34.4% of subjects reported TCV within the unsatisfactory range.

Comparing the thermal satisfaction experienced by subjects across the four places, when sorted by the proportion of individuals feeling comfortable outdoors (TCV > 0), it was observed that Place 2 > Place 4 > Place 3 > Place 1. Notably, the proportion of individuals perceiving Place 2 as comfortable outdoors (37.5%) was 20.5% higher than that observed at Place 1 (17%) (Table 5). It means that people feel that Place 2 is more comfortable outdoors.

To investigate the correlation between thermal sensation votes (TSV) and thermal comfort votes (TCV) across the four locations, the TCV values corresponding to the same TSV within each location were averaged. This yielded the average comfort vote corresponding to each thermal sensation vote, as depicted in Fig. 5. The figure presents the relationship between thermal sensation and thermal comfort votes at the four places.

Figure 5 illustrates that the changing trends of TSV and TCV across the four places were largely similar. In environments that were excessively cold or overheated, the comfort level of individuals in all four places exhibited a decline. By fitting the data using four curves in Fig. 5, the TSV range within which the population in the four locations perceived comfort (TCV ≥ 0) was determined. The TSV change interval under these conditions is detailed in Table 6. Analysis of Table 6 reveals that the outdoor thermal comfort experienced by the population

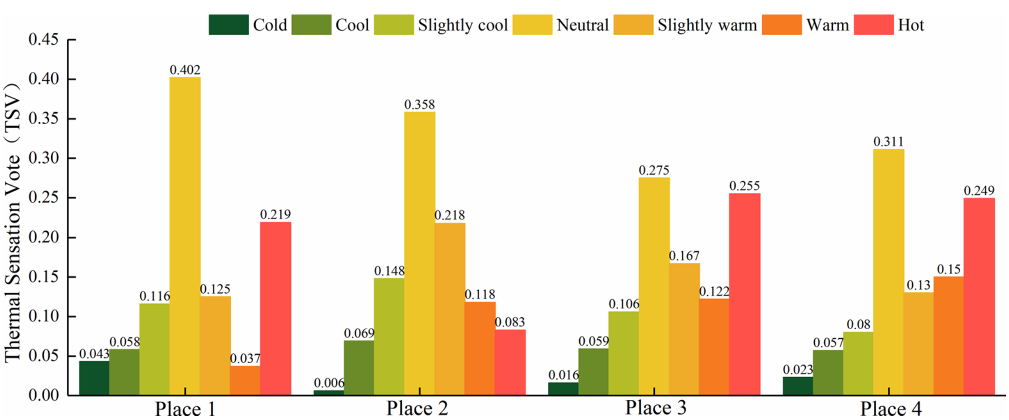


Fig. 3. TSV distribution map of population in four places.

Research location	TSV distribution (%)		
	TSV < 0	TSV = 0	TSV > 0
Place1	21.7%	40.2%	38.1%
Place2	22.3%	35.8%	41.9%
Place3	18.1%	27.5%	54.4%
Place4	16%	31.1%	52.9%

Table 4. TSV distribution table of population in 4 places.

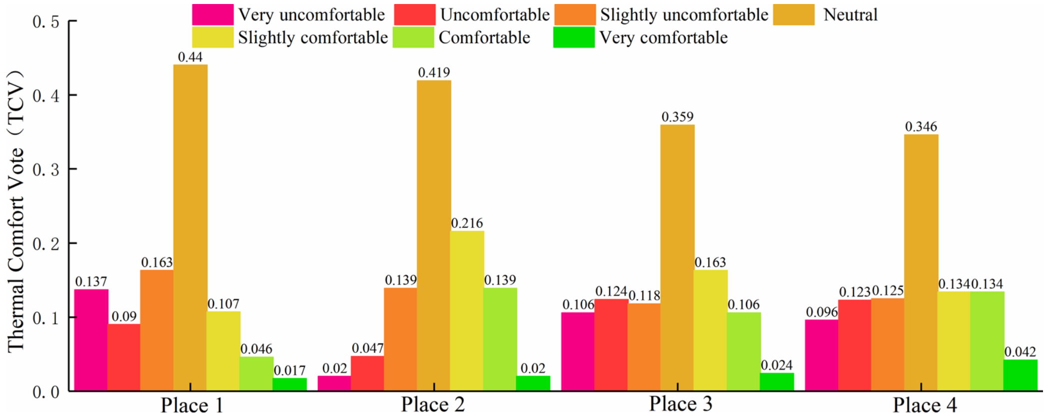


Fig. 4. TCV distribution map of population in four places.

Research location	TCV distribution (%)		
	TCV < 0	TCV = 0	TCV > 0
Place1	39%	44%	17%
Place2	20.6%	41.9%	37.5%
Place3	34.8%	35.9%	29.3%
Place4	34.4%	34.6%	31%

Table 5. TCV distribution table of population in 4 places.

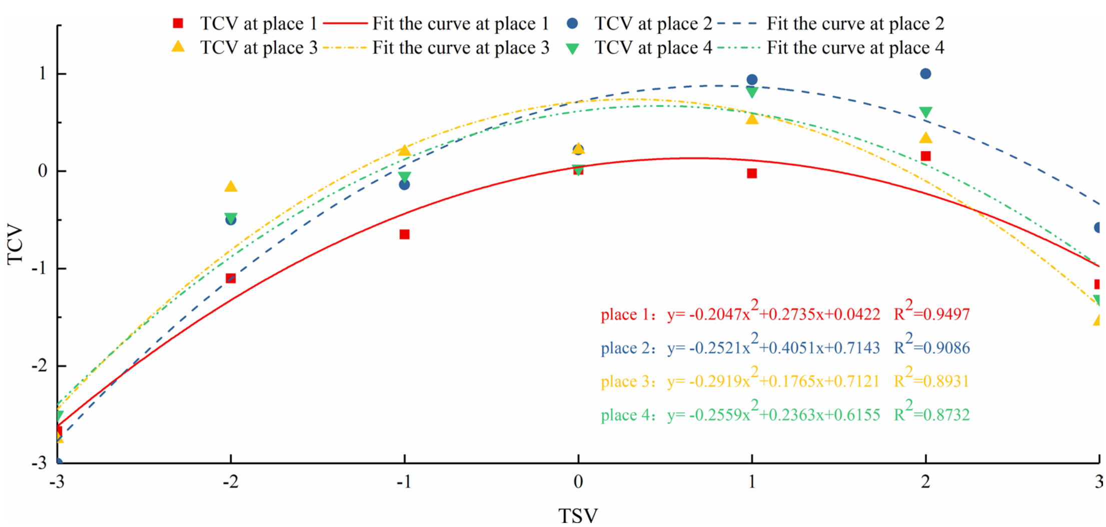


Fig. 5. Relationship between TSV and TCV of the four places.

	TSV	TCV
Place 1	[− 0.31,0.53]	[0,0.13]
Place 2	[− 0.53,1.46]	[0,0.88]
Place 3	[− 0.31,1.41]	[0,0.74]
Place 4	[− 0.35,1.39]	[0,0.71]

Table 6. Change range of TSV in the four places when TCV ≥ 0.

at Place 2 was the most favorable. Conversely, the outdoor thermal comfort at Place 1 was found to be the least satisfactory. This aligns with the conclusions derived from Table 5.

Analysis of heat index indicators

Analysis process of heat index

In this study, linear regression was employed to investigate the relationship between the average heat index (MSET, MUTCI, MPET) and MTSV. The specific steps are as follows:

(1) Meteorological, clothing, and metabolic data were imported into Rayman software to calculate the heat index values (SET, UTCI, PET).
(2) The heat index and TSV values were averaged within 0.5 ℃ intervals to determine the mean heat index values (MSET, MUTCI, MPET) and MTSV.
(3) Linear regression analysis was conducted using SPSS software, with the mean heat index values (MSET, MUTCI, MPET) as the independent variables and MTSV as the dependent variable to establish the relationship model.
(4) The mean-median method was utilized to assess the applicability of the heat index.

Mean-median method

In this project, the mean-median method is used to correct the heat index. Based on the questionnaire data collected from the subjects, the mean and median values of the thermal indices (MSET, MUTCI, MPET) were determined when the subjects reported a neutral thermal sensation. The thermal acceptable range was subsequently established by examining the fitting relationship between the subjects' actual thermal sensations and the thermal indices (MSET, MUTCI, MPET). The inclusion relationship between the mean value, median value, and thermal acceptable range of each thermal index revealed several distinct scenarios:

(1) The entire value range of the mean and median falls within the thermal acceptable range, indicating the applicability of the respective thermal index.
(2) Partial portions of the value range of the mean and median are encompassed by the thermal acceptable range, thereby affirming the suitability of the corresponding thermal index.
(3) None of the values for the mean and median are contained within the thermal acceptable range, signifying the limited applicability of the thermal index under investigation.

SET

Using the mean thermal sensation vote (MTSV) associated with the actual thermal sensation reported by the subjects and the corresponding MSET value, the correlation of MTSV with MSET at the survey site was obtained (Fig. 6). The relationship between actual thermal sensation and SET is given by Eq. (4) to Eq. (7).

$$Place\ 1: MTSV = 0.0972MSET - 1.571\ \left(R^2 = 0.8619\right) \tag{4}$$

$$Place\ 2: MTSV = 0.0846MSET - 1.518\ \left(R^2 = 0.6695\right) \tag{5}$$

$$Place\ 3: MTSV = 0.0858MSET - 1.331\ \left(R^2 = 0.6364\right) \tag{6}$$

$$Place\ 4: MTSV = 0.1042MSET - 1.935\ \left(R^2 = 0.6618\right) \tag{7}$$

Figure 7 displays the range of variation in MSET when the thermal sensation of the population across the four locations reaches a neutral state (MTSV = 0). Employing the box plot technique, the minimum value, lower quartile, median, mean, upper quartile, and maximum value of the MSET data for each location are visually depicted.

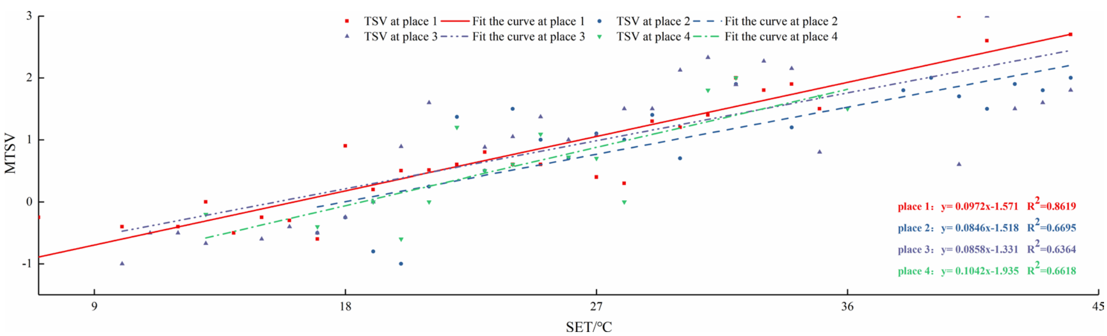


Fig. 6. Change chart of SET and TCV TSV in the four research locations.

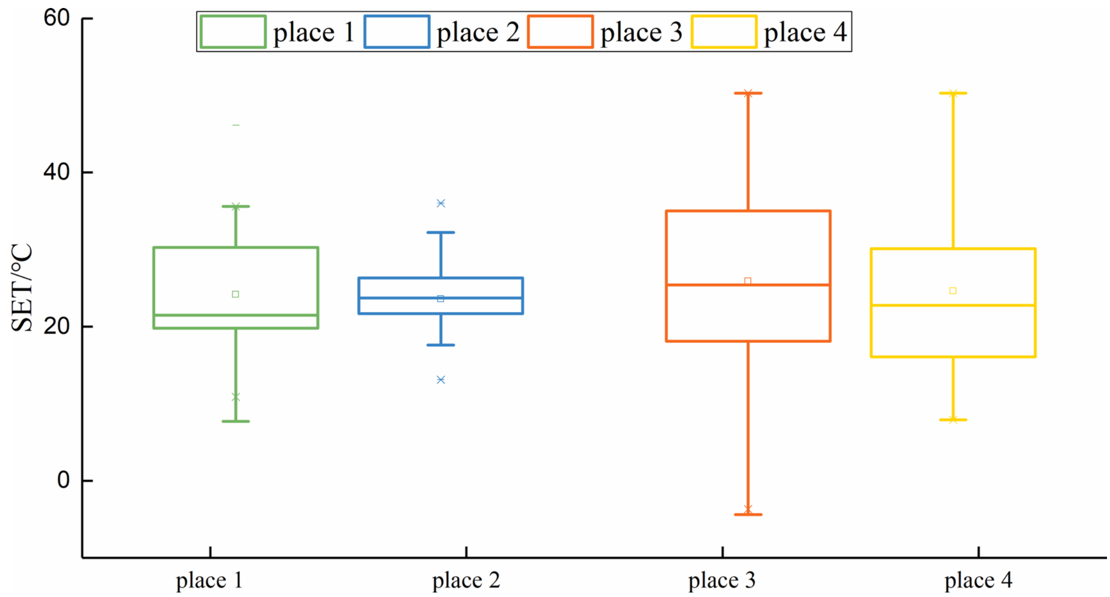


Fig. 7. Box plot of SET variation range at four locations when thermal sensation is neutral (TSV = 0).

To ascertain the suitability of the SET index in the four Places, a comparison was made between the mean and median values of MSET, derived from the box plot analysis (Fig. 7), and the thermally acceptable range presented in Table 7. The SET mean and median values were employed to represent the extent of MSET variation when the actual thermal sensation of the population across the four Places was neutral (MTSV = 0). The neutral MSET was computed using the fitting formulas of MSET and MTSV (Eqs. (4) to (7)), considering -0.5 ≤ TSV ≤ 0.5 as the range of thermally acceptable sensation.

Based on the findings outlined in Table 6, it was determined that MSET demonstrated applicability solely in Place 2, while falling short in Places 1, 3, and 4. Specifically, MSET exhibited an overestimation of the actual thermal sensation experienced by individuals at Places 1, 3, and 4.

UTCI

By employing the mean thermal sensation vote (MTSV) alongside the corresponding MUTCI value, a correlation analysis was conducted to explore the relationship between MTSV and MUTCI at the survey site (Fig. 8). The mathematical Eqs. (8) to (11) were derived to describe the relationship between the actual thermal sensation reported by the subjects and the UTCI value.

$$Place\ 1: MTSV = 0.1386MUTCI - 2.8386\ \left(R^2 = 0.8803\right) \tag{8}$$

$$Place\ 2: MTSV = 0.1673MUTCI - 3.8937\ \left(R^2 = 0.8713\right) \tag{9}$$

$$Place\ 3: MTSV = 0.2246MUTCI - 5.2014\ \left(R^2 = 0.9299\right) \tag{10}$$

$$Place\ 4: MTSV = 0.1811MUTCI - 4.1713\ \left(R^2 = 0.9631\right) \tag{11}$$

Figure 9 shows the variation range of UTCI when the thermal sensation of the population in the four locations is neutral (TSV = 0). The minimum value, lower quartile, median, mean, upper quartile, and maximum value of the UTCI data of the four locations are displayed using the description method of the box plot.

		Mean Value	Median Value	$Value_{fitted\ curve}$ = 0	Thermally acceptable range
MTSV = 0	Place 1	21.6	23.8	16.2	[11.1, 21.3]
	Place 2	23.7	23.8	17.9	[12.1, 23.8]
	Place 3	24.1	24.2	15.5	[9.7, 21.3]
	Place 4	23.2	24.1	18.6	[13.8, 23.4]

Table 7. SET values obtained from mean and median and $Value_{fitted\ curve}$ = 0 method.

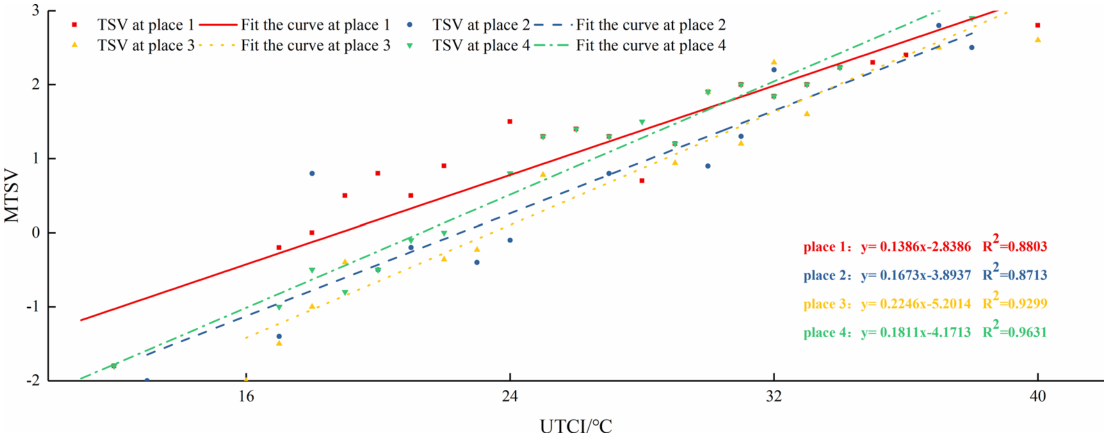


Fig. 8. Changes of UTCI and TCV TSV in the four research places.

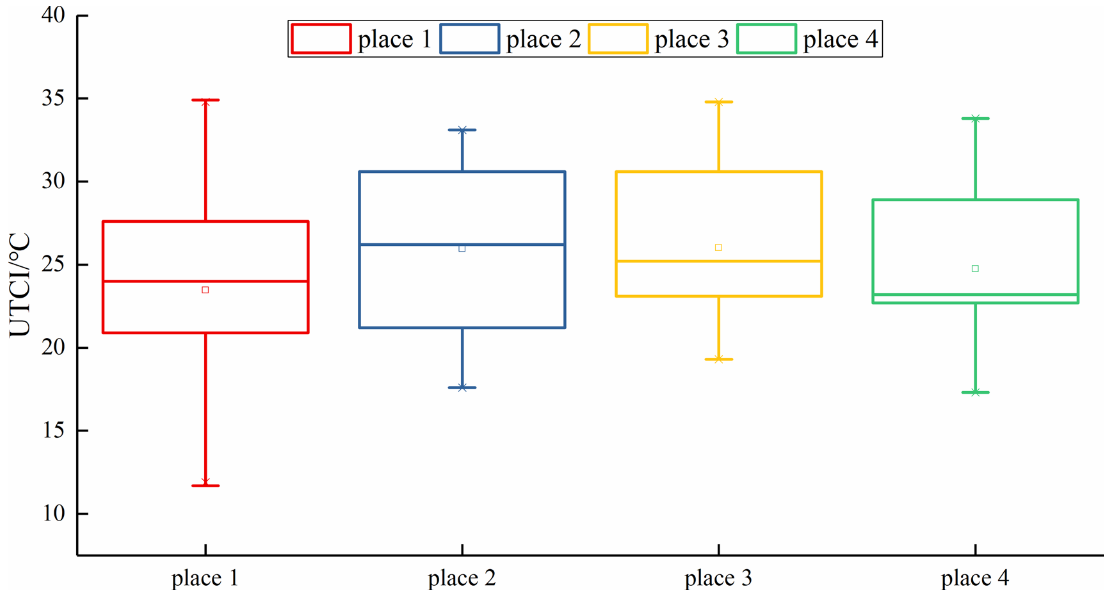


Fig. 9. Box plot of UTCI variation range in four places when thermal sensation is neutral (TSV = 0).

To validate the suitability of the UTCI index in the four Places, a comparison was conducted between the mean and median values of UTCI obtained from the box plot analysis (Fig. 9) under a neutral thermal sensation (TSV = 0) and the thermally acceptable range outlined in Table 8. The mean and median values of UTCI were utilized to represent the range of UTCI variation when the actual thermal sensation experienced by the population in the four Places was neutral (TSV = 0). The neutral UTCI was calculated using the fitting formulas of UTCI and TSV (formulas (8) to (11)), with $-0.5 \leq TSV \leq 0.5$ considered as the range of thermally acceptable sensation.

Based on the analysis results presented in Table 8, it was determined that the UTCI index demonstrates applicability across all four Places.

		Mean Value	Median Value	$Value_{fitted\ curve} = 0$	Thermally acceptable range
MTSV = 0	Place 1	23.9	23.7	20.5	[16.9, 24.1]
	Place 2	25.7	25.6	23.3	[20.3, 26.3]
	Place 3	25.1	25.6	23.2	[20.9, 25.4]
	Place 4	23.2	24.9	23.1	[20.3, 25.8]

Table 8. UTCI values obtained from mean and median and $Value_{fitted\ curve} = 0$ methods.

PET

By examining the mean thermal sensation votes (MTSV) in conjunction with the subjects' reported actual thermal sensations and corresponding MPET values, correlations between MTSV and MPET at the survey sites were established (Fig. 10). The mathematical Eqs. (12) to (15) were formulated to elucidate the relationship between the actual thermal sensation experienced by individuals and the MPET values.

$$Place\ 1: MTSV = 0.1198MPET - 2.2448\ (R^2 = 0.7768) \quad (12)$$

$$Place\ 2: MTSV = 0.1331MPET - 3.0998\ (R^2 = 0.9195) \quad (13)$$

$$Place\ 3: MTSV = 0.1291MPET - 2.7397\ (R^2 = 0.8542) \quad (14)$$

$$Place\ 4: MTSV = 0.1271MPET - 2.8577\ (R^2 = 0.8461) \quad (15)$$

Figure 11 illustrates the range of variation in PET when the thermal sensation of the population across the four places reaches a neutral state (TSV = 0). Utilizing the descriptive box plot method, the minimum value, lower quartile, median, mean, upper quartile, and maximum value of the PET data for each of the four locations are visually represented.

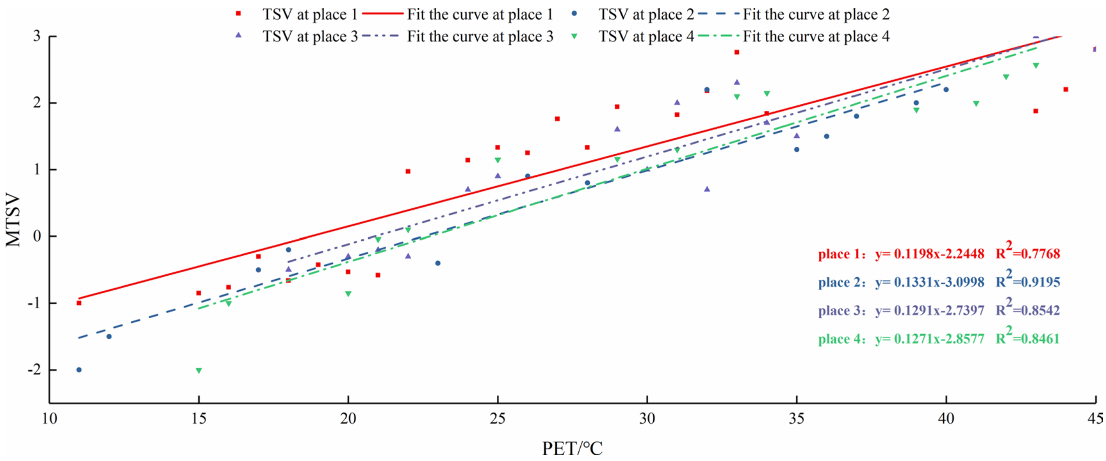


Fig. 10. Changes of PET and TSV in the four research places.

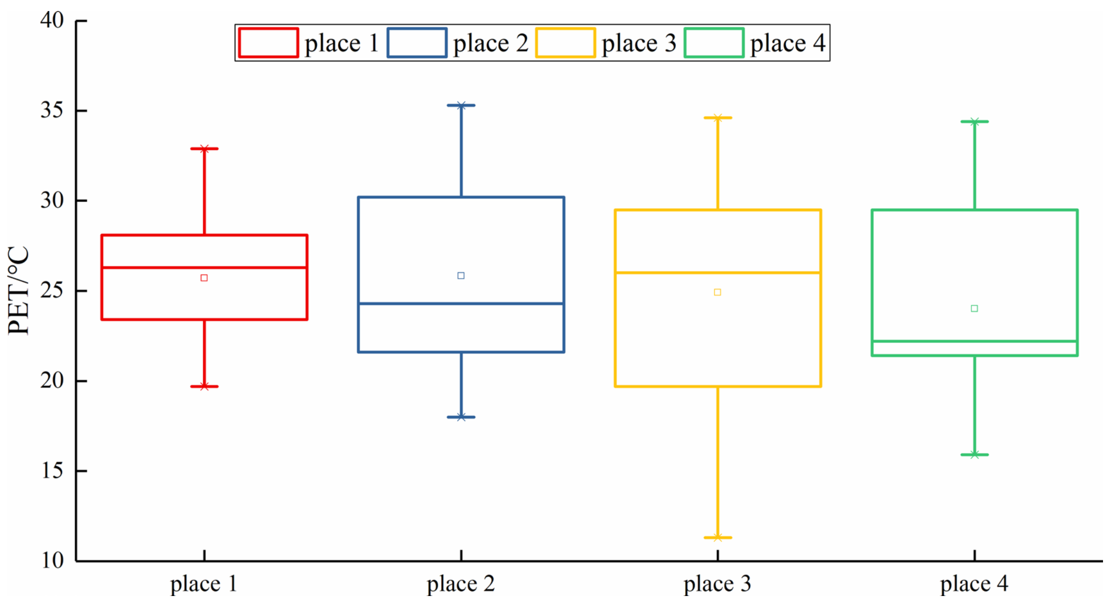


Fig. 11. Box plot of PET change range in four places when thermal sensation is neutral (TSV = 0).

To verify the applicability of the PET index in the four places, a comparison was conducted between the mean and median values of PET obtained from the box plot analysis (Fig. 11) under a neutral thermal sensation (TSV = 0) and the thermally acceptable range provided in Table 9. The mean and median values of PET were employed to describe the range of PET variation when the actual thermal sensation experienced by the population in the four places was neutral (TSV = 0). The neutral PET was calculated using the fitting formulas of PET and TSV (formulas (12) to (15)), with − 0.5 ≤ TSV ≤ 0.5 considered as the range of thermally acceptable sensation.

Based on the analysis results presented in Table 9, it was observed that PET demonstrated applicability in Places 2, 3, and 4. However, at Place 1, PET exhibited discomfort and tended to underestimate the thermal sensation reported by individuals.

Correction of thermal comfort index

Accurate evaluation of outdoor thermal comfort levels necessitates the use of scientific indicators, which in turn requires employing correction methods to refine the thermal comfort index. The slope of the fitting equation, derived through linear regression analysis of MTSV and the heat index, signifies an individual's sensitivity to the thermal environment [39]. Based on the analysis conducted in Section "Analysis of heat index indicators", it has been established that SET and PET tend to underestimate the thermal sensation experienced by the population in certain test places. Consequently, the thermal comfort index correction process is outlined as follows:

Step 1: Establish the fitting equation between MTSV and the thermal comfort index.
Step 2: Determine the upper limit of the subject's thermally acceptable range based on the higher value between the mean and median when the population reports a neutral thermal sensation (TSV = 0).
Step 3: Utilize the control variable method to maintain a constant intercept of the fitting equation, while utilizing the corrected upper limit of the thermally acceptable range as the solution to the fitting equation. This process allows for determining the slope of the revised fitting equation.
Step 4: Conduct scale correction of the thermal comfort index using the revised fitting equation and different TSV values.

Correction of SET index

Based on the analysis conducted in Section "Analysis of heat index indicators", it was observed that SET tended to underestimate the thermal sensations reported by subjects at places 1, 3, and 4. Consequently, corrective measures need to be taken for SET. The relationship between the corrected SET' and the actual thermal sensation is elucidated by Eq. (16) to Eq. (18):

$$Place\ 1 : MTSV = 0.0871\, SET' - 1.518\ \left(R^2 = 0.6695\right) \tag{16}$$

$$Place\ 3 : MTSV = 0.0871\, SET' - 1.518\ \left(R^2 = 0.6695\right) \tag{17}$$

$$Place\ 4 : MTSV = 0.1011\, SET' - 1.935\ \left(R^2 = 0.6618\right) \tag{18}$$

To assess the applicability of the corrected SET' index, the mean-median method was employed, and the test results are presented in Table 10. Upon analyzing Table 10, it becomes evident that the corrected SET' effectively reflects the thermal sensations experienced by the subjects.

Correction of PET index

Based on the analysis conducted in Section "Analysis of heat index indicators", it was determined that PET tended to underestimate the thermal sensations reported by subjects at Place 1. Consequently, corrective measures need

		Mean Value	Median Value	$Value_{fitted\ curve} = 0$	Thermally acceptable range
MTSV = 0	Place 1	26.1	25.6	18.7	[14.6, 22.9]
	Place 2	24.1	25.6	23.3	[19.5, 27.1]
	Place 3	25.6	24.8	21.2	[17.3, 25.1]
	Place 4	21.4	24.2	22.5	[18.5, 26.4]

Table 9. PET values obtained from mean and median and $Value_{fitted\ curve} = 0$ method.

		Mean Value	Median Value	$Value_{fitted\ curve} = 0$	Thermally acceptable range
TSV = 0	Place 1	21.6	23.8	18.1	[12.3, 23.8]
	Place 3	24.1	24.2	17.6	[11.1, 24.2]
	Place 4	23.2	24.1	19.2	[14.2, 24.1]

Table 10. SET' values obtained from mean and median and $Value_{fitted\ curve} = 0$ method.

to be implemented for PET. The relationship between the corrected PET' and the actual thermal sensation is defined by Eq. (19):

$$Place\ 1 : MTSV = 0.1052\,PET' - 2.2448\ (R^2 = 0.7768) \tag{19}$$

To assess the applicability of the corrected PET' index, the mean-median method was employed, and the test results are presented in Table 11. Upon analyzing Table 11, it becomes evident that the corrected PET' accurately reflects the thermal sensations experienced by the subjects.

Discussion

This study evaluates the applicability of three prominent thermal comfort indices—PET, SET, and UTCI—in diverse outdoor environments on a university campus. By examining subjective thermal sensation and comfort votes from students and comparing them with the indices' values, we identified the strengths and limitations of each index in different microclimates. Our findings underscore the complex interactions between environmental variables and human thermal perception, offering valuable insights for urban planners and designers seeking to improve outdoor thermal comfort.

Thermal comfort variations across different outdoor spaces

The results indicate significant spatial variations in thermal comfort across the four study locations. The shaded path (Place 2) was identified as the most comfortable location, with the highest percentage of participants reporting thermal comfort. Conversely, the lakeside area (Place 1) was perceived as the least comfortable, mainly due to the combined effects of higher humidity and solar radiation. These findings align with previous studies highlighting the cooling benefits of shaded environments and the discomfort associated with high humidity and direct sunlight exposure[11–13].

The variation in thermal comfort levels across different microenvironments highlights the necessity of designing outdoor spaces with varied climatic conditions in mind. Urban planners should focus on incorporating shaded areas and optimizing vegetation to alleviate the adverse effects of solar radiation and humidity. This strategy not only enhances thermal comfort but also improves the overall well-being and usability of outdoor spaces[14–17].

Evaluation of SET, PET, and UTCI indices

SET index: limitations and corrections

The SET index consistently underestimated thermal sensations in three out of the four locations (Places 1, 3, and 4). This overestimation suggests that SET may not fully capture the thermal dynamics in environments with significant solar exposure and varying humidity levels. Our findings concur with prior research, which indicates that SET may have limitations in outdoor settings with complex microclimatic interactions[3,18–20].

To address these limitations, we introduced a corrected SET' index, demonstrating improved alignment with the actual thermal sensations reported by participants. This correction process involved recalibrating the SET index based on the mean-median method, resulting in a more accurate representation of thermal comfort in diverse outdoor environments. The corrected SET' provides a more reliable tool for assessing thermal comfort and can guide the design of outdoor spaces that better align with human thermal perceptions[21,22].

PET index: applicability and adjustments

While the PET index showed reasonable applicability in three locations (Places 2, 3, and 4), it failed to accurately reflect thermal sensations at the lakeside area (Place 1). The discrepancy at Place 1 can be attributed to prolonged sun exposure, which PET could not adequately account for. This finding is consistent with the limitations of PET in environments with extreme solar radiation[23].

To enhance the accuracy of PET, we developed a corrected PET' index, which involved adjusting the original PET calculations to better match the observed thermal sensations. The corrected PET' demonstrated improved performance across all locations, providing a more robust tool for evaluating thermal comfort in outdoor settings with varying microclimates.

UTCI index: robustness and reliability

Among the three indices evaluated, the UTCI index exhibited the highest robustness and reliability across all study locations. UTCI effectively captured the thermal sensations reported by participants, reflecting its comprehensive approach to accounting for environmental variables and human physiological responses. The consistent performance of UTCI aligns with its widespread acceptance and validation in diverse climatic contexts[24–26].

		PET at Place 1	PET' at Place 1
TSV = 0	Mean Value	26.1	26.1
	Median Value	25.6	25.6
	$Value_{fitted\ curve} = 0$	18.7	21.3
	Thermally acceptable range	[14.6, 22.9]	[16.6, 26.1]

Table 11. PET' values obtained from mean and median and $Value_{fitted\ curve} = 0$ method.

The strong performance of UTCI underscores its suitability as a primary tool for assessing outdoor thermal comfort in urban environments. Urban planners and designers can confidently use UTCI to inform the development of strategies aimed at improving thermal comfort and enhancing the usability of outdoor spaces[27,28].

Implications for urban planning and design

The findings from this study have significant implications for urban planning and design, particularly in the context of creating thermally comfortable outdoor environments. The demonstrated variability in thermal comfort across different microenvironments highlights the need for context-specific design interventions. Incorporating shaded pathways, optimizing vegetation, and mitigating direct solar exposure are critical strategies for enhancing outdoor thermal comfort[15,16,19,25].

Furthermore, the development and application of corrected thermal comfort indices, such as SET' and PET', provide more accurate tools for evaluating and predicting thermal comfort. These refined indices can guide urban planners in designing outdoor spaces that align more closely with human thermal perceptions, ultimately improving the livability and usability of urban environments[28,29].

Limitations

Despite these findings, our study still has some limitations. First, our study was conducted on campus, and all subjects were healthy young people, so our study did not focus on the effects of age and physical condition on thermal comfort. Second, our study only focused on the physiological responses of the subjects and lacked analysis of the psychological feelings of the subjects. At the same time, this study did not use sensitivity analysis to verify the validity of thermal comfort indicators. Future studies should consider physiological characteristics such as physical condition and age, as well as the psychological expectations of the subjects, and conduct sensitivity analysis under different environmental variables (such as temperature, humidity, wind speed, and solar radiation) to further verify the robustness and applicability of these indices.

Conclusion

This study comprehensively evaluated the applicability of three thermal comfort indices (PET, SET, and UTCI) in different outdoor environments on the campus of Xi'an University, China. Our investigation, based on both objective measurements and subjective evaluations, revealed key insights into the performance and applicability of these indices under different microclimatic conditions. The main findings are as follows:

(1) Significant differences in thermal comfort were observed across the four study sites. The shaded path (Place 2) emerged as the most comfortable environment, while the lakeside area (Place 1) was the least comfortable due to higher levels of humidity and solar radiation. These findings underscore the importance of microclimate factors in influencing thermal comfort and the need for context-specific design interventions in urban planning.

(2) The study found that the SET index consistently underestimated the thermal sensation in sites with higher sunshine and humidity (Places 1, 3, and 4). This limitation necessitated the development of a calibrated SET' index with improved consistency with actual thermal sensations. The PET index showed reasonable applicability in most sites but failed to accurately reflect the thermal sensation in the lakeside area due to prolonged sunshine exposure. The corrected PET' index addresses this issue, providing a more accurate assessment of thermal comfort. The UTCI index demonstrated the highest reliability and robustness across all study locations, effectively capturing the combined effects of various environmental factors on thermal comfort. Its comprehensive approach renders it suitable for diverse climatic environments.

(3) The results of this study hold significant implications for the design of outdoor spaces in urban settings. Incorporating shaded areas, optimizing vegetation, and mitigating direct solar exposure are crucial strategies to enhance thermal comfort and usability of outdoor spaces. The corrected thermal comfort indices (SET' and PET') equip urban planners and designers with more accurate tools to assess and improve thermal comfort, fostering the development of environments more aligned with human thermal perception.

In summary, this study underscores the pivotal role of microclimate conditions in shaping outdoor thermal comfort and demonstrates the utility of the corrected thermal comfort indices in providing accurate assessments. The findings offer actionable insights for urban planners and designers, promoting the creation of more comfortable, livable, and sustainable urban environments.

Data availability

Data will be provided on request.If anyone would like data from this study, please contact the corresponding author of this article.

Received: 3 June 2024; Accepted: 30 August 2024
Published online: 11 September 2024

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Funding
The study was supported by "The Innovation Team of Eurasia University" of Xi 'an Eurasia University (2021XJTD01), Scientific Research Platform of Eurasia University(2022XJPT01),Xi'an Eurasia University Technical Service Special Project (OYKF-2022003) .

Competing interests
The authors declare no competing interests.

Consent to participate
All the authors will participate in the review and publication process.

Consent for publication
All the authors have given their consent to publish this study.

Ethical declarations
The institutional review board of Xi'an Eurasia University approved the study protocol before data collection. Informed consent was obtained for all survey questionnaire participants. All methods were carried out in

accordance with relevant guidelines and regulations. The subjects of the experiments in this paper were clear about the purpose of the experiments before completing the questionnaire and all of them agreed to conduct the experiments.

Additional information

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