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Variations in outdoor thermal comfort in an urban park in the hot-summer and cold-winter region of China

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ABSTRACT

Global warming and rapid urbanization have exacerbated the urban heat island effect. Urban parks contribute to alleviating such an effect and achieving the "carbon emission peak before 2030" and "carbon neutrality before 2060" goals of China. Their popularity is considerably influenced by human thermal comfort. However, limited thermal comfort studies have been conducted in the hot-summer and cold-winter region of China. This study examines human thermal comfort in different landscapes of an urban park in Chengdu and determines the thermal benchmarks. A machine learning (random forest) analysis shows that human thermal sensation is affected by different meteorological factors in different seasons. In addition, the influences of landscape space on human thermal comfort have considerable differences in different seasons. Residents prefer strong solar radiation in winter but fast wind speed in summer. UTCI (universal thermal climate index) is better than PET (physiological equivalent temperature) for outdoor thermal comfort assessment in the study area. This study serves as a valuable baseline and technical reference, contributing to sustainable urban park design.

1. Introduction

Economic globalization has led to rapid urbanization, particularly in developing countries. That is, an increasing number of people have migrated to cities. In the World Cities Report 2020, UN—Habitat states that urban areas accommodate 55% of the population at this stage, and this percentage is predicted to grow to 68% by 2050. Moreover, it predicts that China will add 255 million urban dwellers from 2018 to 2050. China released the primary data of its seventh national census in May 2021, which showed that the percentage of people living in cities was 63.89% at the end of 2020. Indeed, the world is becoming increasingly populated and urbanized. Cities are the home of the vast majority of the world's population, with the consumption of a great deal of energy (about 75 %) and dissipation of considerable heat to the environment (e.g., emitting greenhouse gases) (Nematchoua, Sadeghi & Reiter, 2021).

The positive impact of urbanization on economic development has been widely recognized. Its negative effect (e.g., global warming) should be taken seriously and given special attention as well. In recent years, the occurrence of extreme weather (e.g., superhigh temperature) has increased. The average temperature throughout the year remains high, and the global warming trend will continue. From 1951 to 2018, China's annual average surface temperature showed a notable upward trend with an increasing rate of 0.24 °C per decade. Rising temperatures pose a serious negative impact on human health. High temperatures can cause fatigue and dizziness and increase heart rate. Many severe cases can even be life-threatening and deadly (Wang et al., 2019). Therefore, the Intergovernmental Panel on Climate Change has proposed a goal of confining the global average temperature rise to 1.5 °C.

The concern about the risks posed by climate change to urban livability is now growing (Nogueira, Lima, & Soares, 2020). The intensity of the urban heat island effect is often expressed by the temperature difference between urban and rural areas (ΔT_{u-r}). The increase in the urban temperature is caused by several factors, including increased heat from humans, vegetation deficiency, and radiation absorption (Guo et al., 2020; He, Ding, & Prasad, 2020, 2021; Mathew,

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Abbreviations

ASHRAE	American Society of Heating, Refrigerating and Air-conditioning Engineers
G	Global solar radiation
OTC	Outdoor thermal comfort
OCV	Overall comfort vote
PET	Physiologically equivalent temperature
PTV	Preferred temperature vote
PHV	Preferred humidity vote
PWV	Preferred wind speed vote
PSV	Preferred sunshine vote
RH	Relative humidity
SVF	Sky view factor
T_a	Air temperature
TAR	Thermal acceptability range
T_g	Black globe temperature
T_{mrt}	Mean radiant temperature
T_n	Neutral temperature
NTR	Neutral temperature range
T_p	Preferred temperature
TAV	Thermal acceptability vote
TSV	Thermal sensation vote
UTCI	Universal thermal climate index
v	Wind speed

Khandelwal, & Kaul, 2018; Park, Kim, Lee, Park, & Jeong, 2017; Richards, Fung, Belcher, & Edwards, 2020; Wang & Li, 2016; Yang, Zhou, Wang, & Li, 2020). Moreover, as the urban temperature increases, it is necessary to investigate how to take urban planning and management strategies to solve the problem of urban overheating (He et al., 2021).

As a kind of green infrastructure for cities, urban parks have been shown to create "urban cooling islands" in summer, effectively mitigating the urban heat island effect (Chang, Li, & Chang, 2007; Kong, Yin, James, Hutyra, & He, 2014; Ren, He, Pu, & Zheng, 2018; Yan, Wu, & Dong, 2018). Moreover, they can prevent wind and absorb dust in winter and improve air quality because of their botanical effects (Xing & Brimblecombe, 2020; Xing, Brimblecombe, Wang, & Zhang, 2019). Furthermore, a large number of people are expected to visit parks in winter and summer. Therefore, parks can reduce the use frequency of air-conditioning and other temperature control devices (e.g., electric fan and heating). Energy consumption and carbon emissions can thus be reduced, contributing to the achievement of climate-related aims/targets/goals, such as "carbon emission peak before 2030" and "carbon neutrality before 2060" of China (Jo, Kim &, Park, 2019; Kim, Yi, & Lee, 2019; Wang, Ni, Chen, & Xia, 2019).

This study conducts field surveys in winter and summer in Chengdu People's Park by combining (objective) meteorological measurements and (subjective) questionnaire surveys. Four sites are selected for the field survey. Two popular thermal evaluation indices, namely physiological equivalent temperature (PET) and universal thermal climate index (UTCI), are used to assess the thermal comfort condition of urban parks in the hot-summer and cold-winter (HSCW) region by determining the thermal benchmarks. This study mainly focuses on variations in outdoor thermal comfort (OTC), enriching our previous publication (Zhang et al., 2020).

The contributions of this study are as follows: (1) examining the mechanism through which meteorological parameters affect outdoor thermal perception and determining the importance of different parameters on OTC through machine learning techniques; (2) investigating seasonal differences in the thermal comfort performance of different landscape types within urban parks to ascertain landscape types with the best thermal comfort; and (3) obtaining outdoor thermal benchmark results for the HSCW region through statistical analysis.

2. Literature review

A critical factor in creating a welcoming urban park for city residents is OTC. OTC is developed from indoor thermal comfort by extending the research scope of human thermal comfort from indoor (interior of buildings) to outdoor (open space) (Höppe, 2002). ASHRAE defines human thermal comfort as the psychological state of being satisfied with the environment (ASHRAE, 2017). Two keywords are mentioned: "environment" (objective) and "satisfied" (subjective). Therefore, two streams of the key factors that influence human thermal comfort are the environment and the individual. On the one hand, environmental factors include but are not limited to T_a, G, RH, and v. On the other hand, personal factors include but are not limited to clothing thermal resistance (Clo), activity status (unit: met), age, gender, and thermal experience. As such, the realization of thermal comfort depends on the surrounding environment and personal adaptation. Therefore, combining meteorological field measurements and questionnaire surveys, which integrates subjective and objective factors, is the mainstream research method (Nikolopoulou & Steemers, 2003; Nikolopoulou, Baker, & Steemers, 2001). Over the past 20 years, scholars worldwide have performed numerous field studies in various geographical locations (Nikolopoulou & Lykoudis, 2006; Sharmin, Steemers, & Humphreys, 2019; Villadiego & Velay-Dabat, 2014). The topic of OTC has also attracted the attention of an increasing number of Chinese scholars.

Field survey is now one of the most prominent methods for OTC studies (Cheung & Jim, 2017). We can comprehensively evaluate the thermal perception of local residents for the outdoor environment by collecting objective and subjective data of various open spaces in a climatic region (via meteorological parameter monitoring and questionnaire surveys) and applying different types of statistical analyses to understand outdoor comfort fully. In previous field survey-based OTC studies, four thermal conditions are usually identified to assess people's thermal perceptions: (1)T_n, (2) T_p, (3) NTR, and (4) TAR (Cheung & Jim, 2018; Huang, Hong, Tian, Yuan, & Su, 2021; Ma, Tian, Du, Hong, & Lin, 2021; Yin, Cao, & Sun, 2021; Zhang, Su, Hong, Wang, & Li, 2021). Cheung and Jim (2017) refer to the levels and ranges of these thermal conditions as the "thermal benchmark."

Table 1 summarizes 30 OTC studies recently conducted in China using the field survey method. In China, the number of OTC studies has considerably increased since 2016. This scenario is consistent with the results of the global research. China-based OTC studies are mainly concentrated in the cold region (11 out of 30), followed by the hot-summer and warm-winter (HSWW) region (8 out of 30) and the HSCW region (7 out of 30). The study sites mainly include university campuses (10 out of 30) and urban parks (9 out of 30). Moreover, multiple studies are conducted in one city. This finding indicates that the universality and coverage of OTC studies must be improved.

The formation mechanism of OTC is complex, and OTC cannot be explained by a single thermal environment factor. An, Hong, Cui, Geng, and Ma (2021) found that T_a and T_g are the two main factors influencing the thermal perception of urban dwellers in winter in a cold region. Zeng and Dong (2015) conducted a study in summer in Chengdu and found a strong positive correlation between visitors' TSV and temperature. Zhu, Liang, Sun, and Han (2020) revealed a considerable effect of G on outdoor thermal sensation in winter in a severe cold (SC) region. Lai, Guo, Hou, Lin, and Chen (2014) found that the preferences of urban residents in Tianjin for G, v, and RH are related to temperature. The

Table 1
Summary of OTC studies based on field surveys in China.

Year[1]	Climatic region[2]	Type	Site	TSV Scale	Index	Thermal benchmark T_n[6]	T_p[6]	NTR[6]	TAR[6]	Reference
1996–2005[3]	HSWW	Tourist attraction	Taiwan	ASHRAE 7-point	PET	✓[5]	–	–	✓	(Lin & Matzarakis, 2008)
2006	HSWW	Pedestrian street	Hong Kong	ASHRAE 7-point	PET	✓	–	–	–	(Ng & Cheng, 2012)
2010	HSCW	Various	Changsha	ASHRAE 7-point	PET	✓	✓	–	✓	(Yang, Wong, & Zhang, 2013)
2010	HSCW	Various	Changsha	ASHRAE 7-point	T_{op}[4]	✓	✓	–	✓	(Yang, Lin, Wong, & Zhou, 2014)
2012–2013	C	Urban park	Tianjin	ASHRAE 7-point	PMV, PET, UTCI	✓	–	–	✓	(Lai et al., 2014)
2012	HSCW	Pedestrian street	Chengdu	ASHRAE 7-point	PET	✓	–	–	–	(Zeng & Dong, 2015)
2016–2017	HSWW	University campus	Guangzhou	ASHRAE 7-point	T_{op}, PET	✓	✓	–	✓	(Wang, Ni, Peng, & Xia, 2018)
2016–2017	SC	University campus	Harbin	Other 11-point	PET	✓	–	–	✓	(Chen et al., 2018)
2016–2017	HSWW	University campus	Guangzhou	Other 9-point	PET	✓	✓	–	–	(Fang et al., 2019)
2017	HSWW	Urban park	Hong Kong	Other 9-point	PET, UTCI	✓	✓	✓	✓	(Cheung & Jim, 2018)
2017	SC	Pedestrian street	Harbin	ASHRAE 7-point	UTCI	✓	✓	–	✓	(Jin, Liu, & Kang, 2019)
2017–2018	HSWW	Tourist attraction	Sanya	Other 9-point	PET	✓	–	–	✓	(Shang et al., 2020a)
2017	HSWW	University campus	Guangzhou	Other 9-point	PET, SET*[5], UTCI	✓	✓	–	–	(Wu et al., 2021)
2018	C	Urban park	Xi'an	ASHRAE 7-point	PET, UTCI	✓	–	✓	–	(Xu et al., 2018)
2018	C	Urban park	Xi'an	Modified 7-point	UTCI	✓	–	✓	✓	(Xu et al., 2019)
2018	HSCW	University campus	Mianyang	ASHRAE 7 point	PET, UTCI	✓	–	–	✓	(Huang et al., 2019)
2018	HSCW	Urban park	Mianyang	ASHRAE 7-point	PET	✓	–	–	–	(Cheng et al., 2019)
2018	HSWW	Tourist attraction	Haikou	Other 9-point	PET	✓	–	–	✓	(Shang et al., 2020b)
2011, 17, 18	HSCW	University campus	Wuhan	ASHRAE 7-point	SET*	✓	–	–	✓	(Zhou, Deng, Yang, & Zhou, 2020)
2018–2019	C	Residential community	Xi'an	ASHRAE 7-point	PET	✓	–	✓	✓	(Mi et al., 2020)
2018–2019	C	University campus	Xi'an	ASHRAE 7-point	UTCI	✓	✓	✓	✓	(He, An, Hong, Huang, & Cui, 2020)
2019	HSCW	Urban park	Chengdu	ASHRAE 7-point	PET, UTCI	✓	–	✓	–	(Zhang et al., 2020)
2019	SC	Pedestrian street	Harbin	ASHRAE 7-point	UTCI	✓	–	✓	✓	(Zhu et al., 2020)
2019	C	University campus	Xi'an	ASHRAE 7-point	PET, UTCI	✓	–	✓	–	(Niu, Hong, Geng, Mi, & He, 2020)
2019	C	University campus	Xi'an	ASHRAE 7-point	PET	✓	–	–	✓	(Zhen et al., 2021)
2019–2020	C	Urban park	Beijing, Xi'an, Hami	ASHRAE 7-point	PET, UTCI	✓	–	✓	✓	(An et al., 2021)
2020	C	Urban park	Xi'an	ASHRAE 7-point	PET	✓	✓	✓	✓	(Ma et al., 2021)
2020	C	University campus	Xi'an	ASHRAE 7-point	PET	✓	✓	✓	✓	(Zhang et al., 2021)
2020	C	Urban park	Xi'an	ASHRAE 7-point	UTCI	✓	✓	✓	✓	(Huang et al., 2021)
2020–2021	SC	Commercial district	Harbin	Other 11-point	PET	✓	✓	✓	✓	(Yin et al., 2021)

[1] "Year" is the year of the field survey.
[2] We follow the building climatic region demarcation of China. In the Code for Thermal Design of Civil Building, which was released in 2016, China is divided into five climatic regions, namely Severe Cold (SC), Cold (C), Temperate (T), Hot-Summer and Cold-Winter (HSCW), Hot-Summer and Warm-Winter (HSWW).
[3] The study did not conduct field measurements of climate parameters; the climate data used were from local weather stations.
[4] T_{op} means operating temperature. $T_{op} = (T_a + T_{mrt}) / 2$.
[5] ✓ means the study involved this thermal benchmark.
[6] T_n: neutral temperature. T_p: preferred temperature. NTR: neal temperature range. TAR: thermal acceptability range.

results of previous studies have shown that meteorological parameters have different effects on the thermal sensation of local people in different regions. Therefore, different effects of different parameters on thermal comfort formation must be identified to help designers and builders know the importance of various parameters for future planning and design.

Urban parks are a focus of OTC studies (Zhang et al., 2020). Most related China-based studies are conducted in the cold region (Huang et al., 2021; Ma et al., 2021; Mi, Hong, Zhang, Huang, & Niu, 2020; Xu, Hong, Jiang, An, & Zhang, 2019, 2018), with minimal focus on the HSCW region (Cheng, Gou, Zhang, Feng, & Huang, 2019; Huang, Cheng, Gou, & Zhang, 2019; Zhang et al., 2020). Many studies consider the park as a whole and perform statistical analyses to obtain thermal benchmark results for the entire area (Cheng et al., 2019; Cheung & Jim, 2018; Lai et al., 2014). However, urban parks are composed of many landscape types. Different landscape types have different thermal environment performances, thereby possibly leading to varying results in human thermal comfort (Xu et al., 2018). Therefore, the influence of different landscape types on human thermal comfort in urban parks must be studied from the landscape perspective to provide a theoretical basis and design reference for urban parks in the HSCW region in China.

In past studies, several metrics have been developed to assess the thermal comfort of the outdoor environment, such as THI, PMV, SET*, OUT_SET*, PET, and UTCI (Yin et al., 2021). PET (23 out of 30) and UTCI (13 out of 30) are the most widely used metrics. They use °C as the unit, which is easily understood and comparable across studies. Therefore, PET or/and UTCI are now used extensively to present the analytical results of thermal benchmarks. The most widely used heat sensation scale is the standard ASHRAE 7-point scale developed for indoor use (22 out of 30) (ASHRAE, 2017; Lai et al., 2020). Based on this scale, other scales, such as the 9-point scale (Cheung & Jim, 2018; Fang et al., 2019; Shang, Chen, Cai, & Zhang, 2020a, 2020b; Wu, Zhang, Fang, & Gao, 2021) and 11-point scale (Chen, Xue, Liu, Gao, & Liu, 2018; Yin et al., 2021), have been developed. Among the thermal benchmarks, T_n (30 out of 30) is the most extensively used, followed by TAR (22 out of 30), T_p (13 out of 30), and NTR (12 out of 30). Researchers have adopted different thermal benchmarks to assess thermal comfort for different research purposes. The simultaneous use of the four thermal benchmarks has become popularized in recent years. This scenario indicates the complexity of OTC research, which requires the results of multiple thermal benchmarks and comprehensive comparative analyses to obtain an in-depth understanding of local OTC. Ample evidence documents that people can adapt to various thermal environments, and thermal comfort has a strong connection to the physiological and psychological adaptations of local people over a long time (Huang et al., 2019). Therefore, all thermal benchmarks must be determined and applied locally (Cheung & Jim, 2017). Moreover, developing outdoor thermal benchmarks specifically for urban parks in the HSCW region (e.g., Chengdu) is crucial.

3. Methodology

3.1. Study area

A field survey was conducted in Chengdu (30°39′ N, 104°03′ E), the capital city of Sichuan Province (Fig. 1a). Located in the central part of Sichuan Province, China, Chengdu is the financial, technological, cultural, and educational center of Southwest China and one of the national historical and cultural cities. It is also one of the early developed and prosperous cities in China. The total land area of the city is 14,335 square kilometers, and the altitude of the urban area is more than 500 m. Chengdu has a humid subtropical monsoon climate, with a pleasant climate, abundant precipitation, and abundant sunshine. At the end of 2020, the resident population of Chengdu was 20.9 million, and the urbanization rate was 74.41%. In the Code for Thermal Design of Civil Building (GB 50176–2016) of China, Chengdu belongs to the HSCW region. The climate of the region is characterized by hot and muggy summers and wet and cold winters.

Table 2 shows the monthly average, maximum and minimum T_a, mean RH, and mean v in Chengdu from 1981 to 2010. The mean T_a difference within a year is around 20 °C. The highest temperature occurs in July and the lowest in January. The overall temperature in summer is not high, and the hot season is from June to August. The mean RH was stable throughout the year, with a difference of 10% between the highest and lowest humidity. The mean v did not show significant seasonal variations throughout the year, with the difference between the highest and lowest mean v (0.4 m/s). The maximum values of the mean v were mainly in spring (April-June), and the lowest values were primarily in winter (November-December). This study selected the hottest month of summer (July) and the coldest month of winter (January) for a field survey study to investigate the OTC of urban residents in Chengdu under extreme weather conditions.

Chengdu People's Park (30°39′31″ N, 104°03′20″ E) (see Fig. 1b), located in the city center, is the most representative urban park in Chengdu and is the biggest open landscape and historical park in the city center. Moreover, it is the earliest park in Chengdu and even Sichuan. It is a national "AAAA" (4A-level) tourist attraction. The total area is 112,639 m^2 (about 169 *mu*), and the elevation is 558.4 m. The park is rich in internal landscape elements and spatial types, making it a tractable laboratory to investigate the effects of different landscape types on OTC.

3.2. Experimental design

3.2.1. Field meteorological measurement

After the field survey of the park, four representative meteorological parameter measurement sites (Site A-D) were selected according to the variability of landscape elements and spatial types within the park. The

Table 2
Monthly mean, maximum and minimum T_a, RH, and v in Chengdu from 1981 to 2010.

Month	Mean T_a(°C)	Max. T_a(°C)	Min. T_a(°C)	Mean RH (%)	Wind speed (m/s)
January	5.4^{min}	9.1^{min}	2.6^{min}	83	1.1
February	7.6	11.4	4.8	82	1.2
March	11.3	15.9	7.8	80	1.3
April	16.3	21.5	12.4	79	1.4^{max}
May	20.9	26	17	76^{min}	1.4^{max}
June	23.5	27.6	20.5	81	1.4^{max}
July	25.1^{max}	29.4^{max}	21.9^{max}	85	1.3
August	24.5	29.1	21.4	86^{max}	1.3
September	21.4	25.4	18.7	84	1.2
October	16.9	20.4	14.6	84	1.1
November	12.1	15.8	9.5	83	1.0^{min}
December	6.8	10.3	4.1	83	1.0^{min}

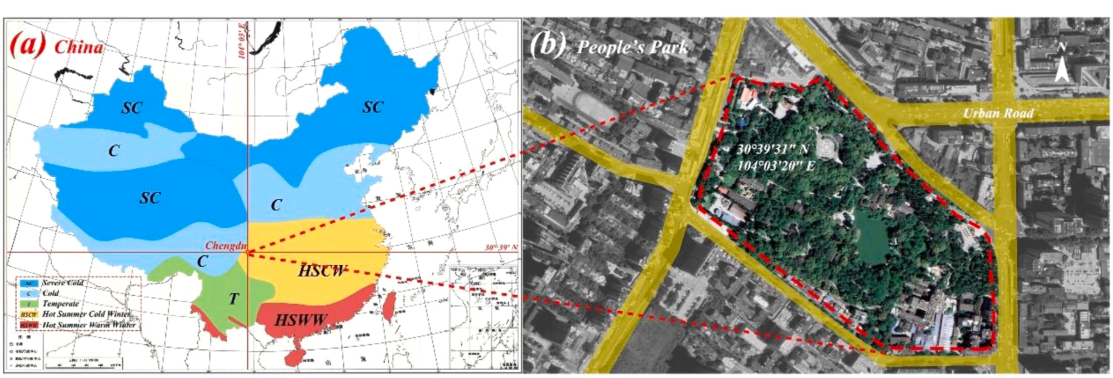

Fig. 1. Location of the study site. (a) Building climate demarcation of China and the location of Chengdu in China (Source: Code for Thermal Design of Civil Building, 2016), (b) Satellite picture of People's Park (Source: Google Earth).

locations of the measurement sites are shown in Fig. 2a. Site A is situated on the east side of the park and is the main entrance to the park. The landscape type is defined as square. The area is underlain by impermeable hard pavement. Artificial ponds and artificial rockery can be found nearby. Site B is situated on the south side of the park, adjacent to the artificial lake inside the park. Its landscape type is defined as lakeside, with nearby vegetation of shrubs and willows. Site C is situated in the center of the park. Its landscape type is defined as a lawn with tall deciduous trees such as sycamores nearby. Site D is situated on the northwest side of the park. Its landscape type is defined as woods, surrounded by tall evergreen trees and abundant shrubs and herbaceous plants.

The landscape type of the measurement sites is described within an area with a radius of 10 m centered on the sites. Fig. 2b shows the field reality photos of the four measurement sites. Fisheye images of the four sites were taken in winter and summer to determine the degree of shading in the landscape space. SVF was calculated for each measurement site using RayMan software (Cheung & Jim, 2018; Xu et al., 2018, 2019) (see Fig. 2c and Fig. 2d).

The field survey was conducted from January 14 to 16, 2019 (09:00–18:00) and July 24–26, 2019 (07:00–20:30). The measurement dates were chosen from the three days of the coldest month and the three days of the hottest month in Chengdu. The measurement times were determined by considering the sunrise and sunset times. Each measurement site was arranged with the same meteorological parameter measuring instruments, and the detectors of the measuring instruments were placed at the height of 1.5 m. The measurement data were recorded every 15 min. The meteorological parameters measured in the field survey included T_a, RH, T_g, v, and G. Table 3 shows the basic information of the measurement instrument, including the model number, measurement content and range, accuracy and resolution, and other instrument parameters. All instruments used in the study are compliant with ASHRAE Standard 55–2017 (ASHRAE, 2017).

3.2.2. (Subjective) Questionnaire survey

The questionnaire has three main parts. The first part records the information of the survey, such as location, date, and time. The second part is the collection of thermal perception data, including respondents' thermal sensation, thermal comfort, thermal acceptability, and meteorological parameter preferences (e.g., temperature and sunshine). Table 4 lists various scales used in the survey to assess heat perception. The third part records the interviewees' basic personal information, such as age, gender, weight, clothing, activity status, and past heat experiences, because the interviewees' personal factors are a predictor of heat perception.

The questionnaires were conducted in the vicinity of the measurement site (within a 5 m radius area with the measurement site as the center of the circle). The interviewees were required to stay at the measurement site for at least 15 min to ensure that the interviewees' thermal perception was truly influenced by the microclimate in the vicinity of the measurement site. The interviewees who participated in the questionnaire were randomly selected to ensure that the study could collect the most comprehensive data on the thermal perception of local residents. A total of 419 valid questionnaires were collected, with 199 in winter and 220 in summer. The meteorological data measured in the field and the data from the questionnaire were unified and organized for subsequent statistical analysis.

Table 3
Instruments used for measurement.

Instrumentation	Parameter	Range	Accuracy	Resolution
Testo, 174H-Mini	Air temperature (T_a)	−20 °C to + 70 °C	± 0.5 °C	0.1 °C
	Relative humidity (RH)	0 to 100 %	± 3%	0.1 %
TENMARS, TM-404	Wind speed (v)	0 to 25 m/s	± 2%	0.1 m/s
JT TECH., JRT04	Black globe temperature (T_g)	−20 °C to 125 °C	± 0.2 °C	0.1 °C
JT TECH., JRT05	Global solar radiation (G)	0 to 2000 W/m^2	≤ ±2%	1 W/m^2

Table 4
The scale used in the questionnaire survey.

Questions	Answer options
TSV	Cold, Cool, Sightly cool, Neutral, Slightly warm, Warm, Hot
OCV	Uncomfortable, Neutral, Comfortable
TAV	Absolutely unacceptable, Unacceptable, Acceptable, Absolutely acceptable
PTV	Warmer, No change, Cooler
PHV	Less humid, No change, More humid
PWV	Slower, No change, Faster
PSV	Weaker, No change, Stronger

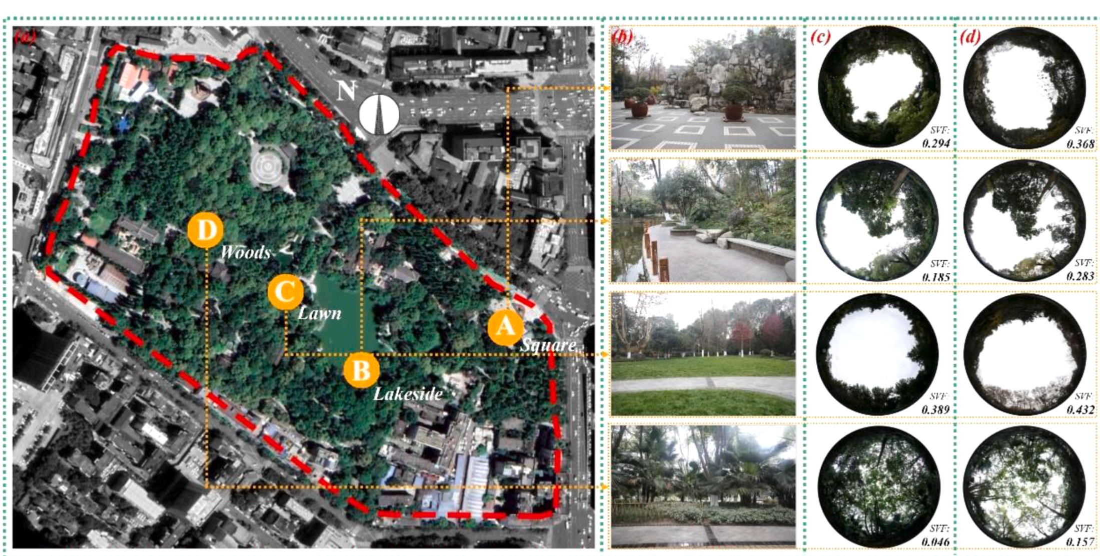

Fig. 2. Field survey site information. (a) Location, (b) Field photos, (c) Fisheye photos in summer, (d) Fisheye photos in winter. Source: (Zhang et al., 2020).

3.3. Thermal comfort indices

In this study, PET and UTCI were used as the thermal comfort evaluation indices to quantify human heat stress and express thermal benchmark results to assess OTC.

3.3.1. PET

PET is more intuitive than other thermal indices (e.g., PMV, SET*). It also has the advantage of being easy to understand. The value can correspond to the thermal perception and can be translated into an equivalent rating of physiological stress. In addition, PET has an easily identifiable unit of °C. Thus, understanding thermal comfort is simplified for city dwellers and urban builders. Table 5 shows the range of PET values in relation to thermal perception and physiological stress.

3.3.2. UTCI

UTCI is an index proposed by the International Society for Biometeorology (ISB) based on the concept of equivalent temperature. The calculated UTCI values or data points are equivalent temperatures obtained from a set of air temperature, radiation, wind, and humidity data that correspond to air temperatures under radiation, humidity, and wind speed reference conditions. The relevant assessment scales are developed based on simulated physiological responses and include ten categories ranging from extreme cold stress to extreme heat stress (Table 6).

3.3.3. Calculation of the thermal index

The latest version of the freeware program RayMan, namely RayMan Pro, was applied to calculate PET and UTCI. The calculation of both indices required the input of the four meteorological parameters (T_a, RH, v, and T_{mrt}) and two personal factors, namely metabolic rate and clothing insulation. The meteorological parameters T_a and RH can be entered as directly measured data, whereas v and T_{mrt} must be calculated. The metabolic rate and the clothing insulation are set to default values, which are PET (80 W, 0.9 clo), and UTCI (135 W/m^2, 0.9 clo).

The calculation of T_{mrt} is expressed as (Cheung & Jim, 2018):

$$T_{mrt} = \left[\left(T_g + 273.15\right)^4 + \frac{1.1 \times 10^8 V_a^{0.6}}{\varepsilon D^{0.4}}\left(T_g - T_a\right)\right]^{\frac{1}{4}} - 273.15 \quad (1)$$

where D is the globe diameter (= 150 mm in this study), and ε is the globe emissivity (0.95).

PET requires v to be measured at 1.1 m, whilst UTCI requires v to be measured at 10 m. Due to the experimental equipment, it is difficult to obtain wind speeds at 1.1 m and 10 m. Therefore, Bröde et al. (2012) suggested that the logarithmic wind profile can be used to approximate the desired wind speed at x m (v_x).

$$v_x = v_m \times \frac{log\left(\frac{x}{z_0}\right)}{\log\left(\frac{m}{z_0}\right)} \quad (2)$$

where v_m is the wind speed at measurement height, m is wind speed measurement height (m), and z_0 is 0.01 m for an urban street environment (Bröde et al., 2012).

Table 5
Classification of thermal sensation and stress on the PET scale.

PET (°C)	Thermal perception	Grade of physical stress
> 41	Very hot	Extreme heat stress
35 to 41	Hot	Strong heat stress
29 to 35	Warm	Moderate heat stress
23 to 29	Slightly warm	Slight heat stress
18 to 23	Neutral (Comfortable)	No thermal stress
13 to 18	Slightly cool	Slight cold stress
8 to 13	Cool	Moderate cold stress
4 to 8	Cold	Strong cold stress
≤ 4	Very cold	Extreme cold stress

Table 6
Thermal stress classification for UTCI.

UTCI (°C)	Thermal stress category
≥ +46	Extreme heat stress
+38 to +46	Very strong heat stress
+32 to +38	Strong heat stress
+26 to +32	Moderate heat stress
+9 to +26	No thermal stress
0 to +9	Slight cold stress
−13 to 0	Moderate cold stress
−27 to −13	Strong cold stress
−40 to −27	Very strong cold stress
< −40	Extreme cold stress

3.4. Thermal comfort benchmarks

3.4.1. T_n

T_n is the temperature level at which people feel neither cold nor hot, that is, the temperature corresponding to the “neutral” option in TSV. The literature review revealed that the vast majority of existing studies used linear regression methods to obtain T_n (in Table 1, 26 out of 30). The regression function was obtained by linearly fitting the mean TSV (averaged at 1.0 bin) to the temperature indices (PET, UTCI, others). The value of X corresponding to the regression function $Y = 0$ (Y is the mean TSV) is T_n. In this study, linear regression is also considered to obtain T_n.

3.4.2. NTR

NTR is an extension of T_n. Based on the regression equation of the neutral temperature, the X value predicting $Y = [-0.5, 0.5]$ is calculated, and the obtained X range is NTR. This method is the most widely used (in Table 1, 10 out of 13 terms).

3.4.3. T_p

T_p is the thermal environmental condition under which most of the interviewees prefer neither warmer nor cooler temperatures than the present temperature. The question “What is your expectation of the current thermal environment?” was set at the beginning of the questionnaire design to assess the preferred temperature. The questionnaire was designed by answering “warmer” or “cooler.” Then, the ratio of “warmer” to “cooler” was calculated by 1 °C bin. Then we used logistics regression to fit the model. The intersection point is the preference value. This method was the one that formed the consensus. The 12 studies involving preferred temperatures in Table 1 all used this method to determine the preferred temperature. This study did not consider exploring the preferred temperature in the experimental design. Therefore, the results of this study do not address the preferred temperature. The preferred temperature is discussed to obtain comprehensive knowledge and understanding of the thermal benchmarks for application in future studies.

3.4.4. TAR

TAR is the temperature range that more than 80% of the respondents find acceptable. In other words, only 20% of the respondents find the range unacceptable. The 80% acceptability is defined by ASHRAE Standard 55 (ASHRAE, 2017). The acceptable temperature range is determined by classifying the acceptability poll results by 1 °C (temperature index: PET, UTCI, etc.) and counting the average acceptability (%) separately. Then, a quadratic polynomial is fitted to the mean acceptability and temperature index to obtain a regression function. The dual solution of X for $Y = 80\%$ is the acceptable temperature range. This method has been widely used. Of the 18 studies involving TAR in Table 1, 16 use the regression method. Therefore, the quadratic polynomial regression method is used in this study to determine TAR.

4. Results

4.1. Summary of measurement and questionnaire

Outdoor meteorological parameters were measured for 6 days in winter and summer. Table 7 collates the T_a, RH, T_g, v, and G at each measurement site during the measurement period and presents the mean, maximum and minimum values of each meteorological parameter for each day. The mean T_a in winter and summer are 9.6 °C and 30.0 °C, respectively. The mean RH and the mean v during the measurement period are also reduced compared with the statistics in Table 2. This finding indicates that the urban thermal environment has changed with the development of the city and that the air moisture content and the ventilation efficiency have decreased because of the increase in the number of buildings. In terms of T_a, the minimum temperature in winter is 5.2 °C, and the maximum temperature in summer is 37.9 °C, with a range of 32.7 °C, indicating a considerable difference in climate between different seasons in the HSCW region. In terms of RH, the difference between the maximum (87.9%) and minimum (45.4%) values is approximately 40% in both winter and summer. This finding indicates that the RH varies considerably throughout the day and is likely to be an important factor affecting human thermal comfort. The variation of v in winter and summer is not considerable and is a relatively stable meteorological parameter. The mean wind speed in this survey is much smaller than the data in Table 2. The reason is that the wind speed was assessed at the height of 1.5 m, at which the wind was blocked by buildings and vegetation. T_g and G from winter to summer have considerable differences. In general, most of the meteorological parameters show seasonal variations.

As revealed before, 419 valid questionnaires were collected for this study. Table 8 summarizes the personal information data of the interviewees. The average age of the respondents was greater in winter (46 years) than in summer (36.5 years). This finding suggests that urban parks are more attractive to older people in winter than in summer. The gender distribution was nearly even, with women accounting for 53.94% and men constituting 46.06%. The height-to-weight ratio of the interviewees was in line with the local average. All interviewees have lived in the Chengdu metropolitan area for more than a year and have adapted to the local climate. They could select clothing based on climate characteristics and objectively and accurately assess the outdoor thermal environment.

TSV can express the interviewees' perception of the outdoor thermal environment at that time and is the most intuitive data to understand human thermal comfort. Meteorological parameters show seasonal changes. Thus, people's thermal sensation also shows differential changes in different seasons. Fig. 3a shows the distribution of thermal sensation during the survey in winter and summer. The horizontal coordinates represent the percentage of votes for different thermal sensations, and the vertical coordinates represent different thermal sensations in the ASHARE 7-point scale.

In terms of thermal sensation width, the TSV range was [−3, +1] in winter and [−2, 0] in summer, indicating that thermal sensation was more concentrated in summer. The percentage of votes for 0 ("neutral") in summer (38.2%) was higher than that in winter (28.1%). The percentage of votes for +1 ("slightly warm") was 34.1% in summer, and that for -1 ("slightly cool") was 34.2% in winter. The percentage of +2 ("warm") in summer (27.7%) was considerably lower than the percentage of -2 ("cool") in winter (34.2%). The results of TSV indicate that interviewees rated the thermal environment in summer considerably higher than that in winter.

Table 8
Summary of personal information of the interviewees in the questionnaire.

Season	Gender	No. of people	Average age	Average height (cm)	Average weight (kg)	Average clothing (clo)
Winter	Male	95	45	168.3	68.9	1.52
	Female	104	47	162.9	60.3	1.59
Win. avg.	–	–	46	165.6	64.6	1.56
Summer	Male	98	35	171.1	67.3	0.45
	Female	122	38	164.6	59.8	0.58
Sum. avg.	–	–	36.5	167.9	63.6	0.52

This finding on TSV is corroborated by the OCV results shown in Fig. 3b, where the percentage of votes ≥ 0 is 77.3% in summer and 70.9% in winter. Fig. 3c shows the results of the interviewees' voting for thermal acceptability in winter and summer. The percentage of voting acceptable in summer is 71.4%, which is extremely close to the percentage of voting acceptable in winter (70.9%). The results indicate that the respondents are consistent in adapting to the local thermal environment in winter and summer. In terms of meteorological parameter preference voting, the interviewees' preference for temperature varies across the season, with the majority preferring warm winters (76.4%) and cold summers (73.6%) (See Fig. 3d). Fig. 3e shows the interviewees' preference for RH. The voting results are relatively stable, with most of them voting "no change" (78.4% in winter, 88.6% in summer), indicating that the respondents do not perceive considerable changes in RH.

Regarding PWV (Fig. 3f), the voting results in winter (60.8%) mainly focused on "no change," whereas those in summer mainly focused on "faster" (86.8%), indicating that the respondents show strong demand for wind speed in summer. The reason is that T_a and RH are high in summer, and the human skin heat dissipation condition is poor. In addition, v is needed to speed up the skin heat dissipation efficiency and achieve the thermal comfort state. In terms of sunshine preference (Fig. 3g), most people wanted increased sunshine in winter (81.4%), and more than 50% voted "no change" in summer (63.2%). The reason is that Chengdu residents do not receive sunlight often because of few sunny days and are much inclined to receive sunlight during the cold-winter months to improve the feeling of heat.

4.2. Relationship of meteorological factors and TSV

Machine learning techniques have been widely adopted to identify the relationship among a series of factors. Unlike traditional regression-based methods relying on a pre-determined functional form (e.g., linear regression, Poisson regression, negative binomial regression, log-linear

Table 7
Summary of meteorological parameters measured during field survey.

Date	T_a (°C)			RH (%)			T_g (°C)			v (m/s)			G (W/m^2)		
	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.
2019/1/14	9.9	13.9	6.9	62.6	79.4	51.0	10.2	14.5	7.0	0.2	0.7	0.0	64.3	175.0	8.0
2019/1/15	9.7	12.2	7.1	45.4	74.4	34.2	10.0	12.4	7.0	0.2	0.8	0.0	71.1	138.0	10.0
2019/1/16	9.3	18.1	5.2	57.9	77.4	33.4	9.7	19.4	4.7	0.2	0.6	0.0	63.4	176.0	8.0
Win. avg.	9.6	14.7	6.4	55.3	77.1	39.5	10.0	15.4	6.2	0.2	0.7	0.0	66.3	163.0	8.7
2019/7/24	30.2	37.5	25.2	70.2	87.9	46.5	31.0	42.4	25.3	0.1	0.7	0.0	103.8	652.0	0.0
2019/7/25	29.3	36.7	25.0	69.2	87.9	46.5	30.2	39.1	25.1	0.1	0.8	0.0	105.6	650.0	0.0
2019/7/25	30.5	37.9	26.2	68.0	86.7	45.3	31.4	40.3	26.3	0.1	0.8	0.0	115.6	661.0	0.0
Sum. avg.	30.0	37.4	25.5	69.1	87.5	46.1	30.9	40.6	25.6	0.1	0.8	0.0	108.3	654.3	0.0

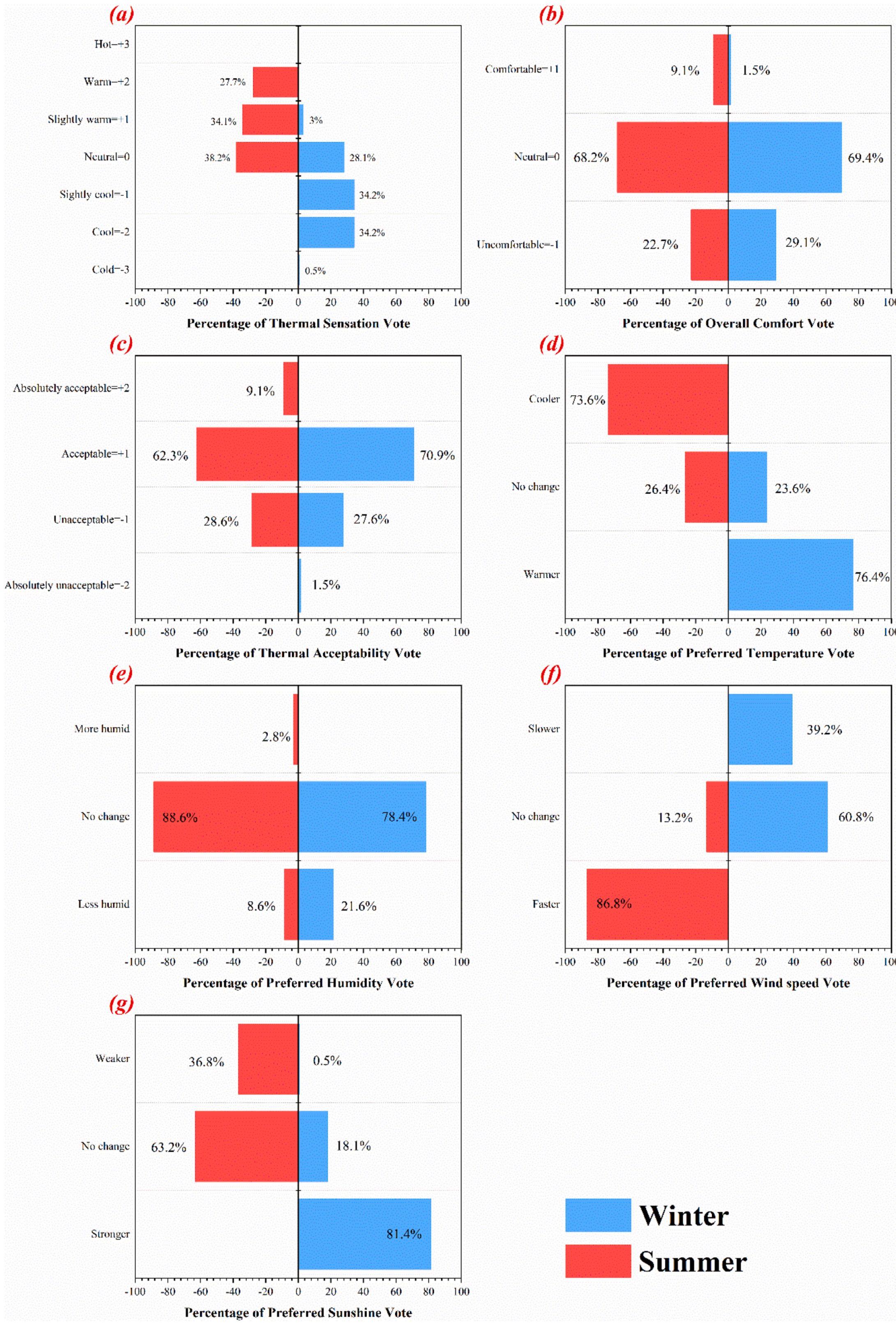

Fig. 3. Summary of answers to subjective thermal perception questions in winter and summer. (a) TSV, (b) OCV, (c) TAV, (d) PTV, (e) PHV, (f) PWV, (g) PSV.

modeling, and discrete choice modeling) (Huo et al., 2021; Yang, Chau, Szeto, Cui, & Wang, 2020), machine learning techniques do not pre-specify an algebraic form of a relationship between a dependent variable and independent variables (regressors) (Liu, Wang, & Xiao, 2021; Xiao, Lo, Liu, Zhou, & Li, 2021). Therefore, in this study, the random forest, a popular and powerful supervised machine learning technique, is used to determine the association between TSV and its correlates. As its name intuitively suggests, the random forest does not build a single decision tree (as in the Classification and Regression Tree model, well-known as the “CART model”) but creates a forest with a series of decision trees (Fig. 4). Major voting and averaging are adopted to obtain the final result for classification problems and regression problems, respectively.

Two random forests are created to estimate the relative importance of each covariate in predicting TSV separately for winter and summer. Table 9 shows the results. In the studied park, TSV in winter is mainly predicted by RH and T_a. This observation indicates that RH and T_a are important for people's thermal sensation and agrees with our expectations. In summer, TSV is predominantly predicted by T_a (constituting over 70% of importance). This scenario indicates that in summer, air temperature is closely associated with people's thermal sensation. An interesting finding is that the thermal sensation is shaped by different factors in different seasons. It has rarely been pointed out in previous studies and serves as a contribution of this study. Notably, the machine learning modeling results should be interpreted cautiously because of limited sample sizes. More empirical studies conducted in diverse sites are, therefore, needed to confirm or disprove our conclusions.

Table 9,
Random forest modeling results for winter and summer.

Variable		T_a (°C)	RH (%)	T_g (°C)	v (m/s)	G (W/m^2)
Relative importance	Winter	0.245	0.290	0.233	0.051	0.181
	Summer	0.735	0.052	0.130	0.012	0.071

4.3. *Thermal comfort of four landscape spaces*

4.3.1. *Analysis of meteorological parameters*

Table 10 shows the meteorological parameters for the four measurement sites during the winter and summer field surveys. In winter and summer, the mean T_a at Site B is the highest (Winter: 10.3 °C, Summer: 31.0 °C) because Site B is next to an artificial lake. The calm water surface forms a mirror effect, reflecting a large amount of solar radiation into the environment. Another reason is the large specific heat capacity of water. The water can store heat and is slowly exothermic. Thus, the surrounding environment temperature is maintained at a high level. The mean, maximum, and minimum T_a at Site D are the lowest among the four sites in winter and summer because Site D has the highest degree of shading and the lowest SVF (0.157 in winter, 0.046 in summer) among the four sites. Thus, Site D receives the least amount of solar radiation, keeping T_a at a low level. The minimum temperatures at the four measurement sites in winter and summer are highly similar, around 5 °C in winter and 25 °C in summer. This finding indicates that the minimum temperatures in the park are not influenced by landscape variability and that the temperatures in the park reach a consistent level at certain times of the day. The lowest RH, Site D (Winter: 42.9%. Summer: 60.6%), is the highest among all four measurement sites, in winter and summer. This observation indicates that dense vegetation has good water retention and that the shading effect of plants reduces the evaporation of water from the environment. The maximum RHs at the four measurement sites are highly similar (around 77% in winter and 80% in summer), indicating that the maximum RH reaches the same level as the minimum T_a at some time of the day.

T_g is the combined result of G and T_a. The minimum T_g values of the four measurement sites were compared with one another. The results indicate that these values are highly similar, explaining the similarity of results for the minimum T_a. In particular, solar radiation is an important factor in determining the increase of T_a. In the absence of solar radiation or low solar radiation, T_a in the park is maintained at the same low level. The variability of *v* at the four measurement sites is not considerable and is consistent with the results presented in Table 4. Although solar radiation affects the change in T_a, it is not the only influence; the change in T_a and T_g does not coincide with the change in G. The variation of meteorological parameters is influenced by various factors, which is one of the reasons why the formation mechanism of OTC is complex.

In summer, each meteorological parameter of Site D has the coolest characteristic. In winter, the meteorological parameters of Sites A, B, and C are close. Determining the landscape type with the warmest characteristics is complex.

4.3.2. *Analysis of subjective questionnaire vote*

Table 11 summarizes the results of the subjective questionnaire for the four sites during the winter and summer field surveys. In terms of TSV, the highest percentage of votes for "neutral" in winter was for Site C (68%), and the highest percentage of votes for "neutral" in summer was for Site D (60%). In terms of OCV, the highest percentage of "neutral" votes in winter was for Site C (100%), followed by Site B (95.56%), and the highest percentage of "neutral" votes in summer was for Site D (80%). In terms of TAV, the highest percentage of votes for "acceptable" in winter was for Site B (100%), followed by Site C (98%),

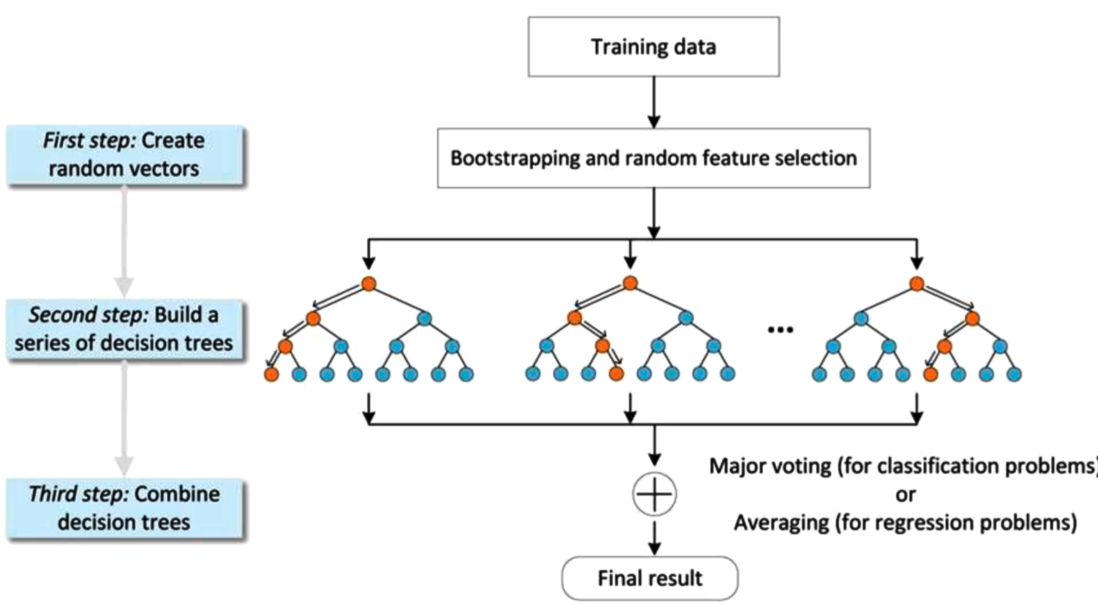

Fig. 4. Workflow of the random forest.
Source: (Cheng, De Vos, Zhao, Yang, & Witlox, 2020; Yang, Ao, Ke, Lu, & Liang, 2021).

Table 10
Summary of meteorological parameters of the sites in winter and summer.

Season	Site	T_a (°C)			RH (%)			T_g (°C)			v (m/s)			G (W/m^2)		
		Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.
Winter	A	9.7	12.2	5.5	54.6	79.4	35.9	10.1	13.5	5.5	0.1	0.6	0.0	74	168	8
	B	10.3	16.2	7.4	53.2	77.0	34.2	10.5	16.4	4.8	0.3	0.8	0.0	80	176	13
	C	10.1	18.1	5.2	54.1	77.2	33.4	10.5	19.4	4.7	0.2	0.6	0.0	75	170	10
	D	8.5	9.8	5.2	59.4	77.4	42.9	8.6	10.1	5.3	0.1	0.4	0.0	36	74	10
Summer	A	30.8	36.3	25.8	65.8	84.4	47.7	32.4	42.4	25.7	0.1	0.8	0.0	124	661	0
	B	31.0	37.9	25.7	68.4	87.3	45.6	31.5	40.3	25.6	0.1	0.8	0.0	125	661	0
	C	30.3	36.9	25.2	68.0	87.5	45.3	31.7	40.3	25.6	0.1	0.8	0.0	125	661	0
	D	27.8	29.9	25.0	74.5	87.9	60.6	27.9	30.6	25.1	0.1	0.2	0.0	59	174	0

Table 11
Summary of the questionnaire survey at measuring sites in winter and summer.

Questions	Answers	Winter (Percentage of votes)				Summer (Percentage of votes)			
		A	B	C	D	A	B	C	D
TSV	Cold=−3	0	0	0	2	0	0	0	0
	Cool=−2	42.59	26.67	2	64	0	0	0	0
	Sightly cool=−1	50	53.33	22	12	0	0	0	0
	Neutral=0	5.56	20	68	20	52.73	20	20	60
	Slightly warm=+1	1.85	0	8	2	20	45.45	38.18	32.73
	Warm=+2	0	0	0	0	27.27	34.55	41.82	7.27
	Hot=+3	0	0	0	0	0	0	0	0
OCV	Uncomfortable=−1	42.59	0	0	70	38	24	24	5
	Neutral=0	57.41	95.56	100	28	47	76	69	80
	Comfortable=+1	0	4.44	0	2	15	0	7	15
TAV	Absolutely unacceptable	1.9	0	0	4	0	0	0	0
	Unacceptable	42.6	0	2	62	38	38	31	7
	Acceptable	55.5	100	98	34	49	62	60	78
	Absolutely acceptable	0	0	0	0	13	0	9	15
PTV	Warmer	94.4	64.4	46	98	0	2	0	0
	No change	5.6	35.6	54	2	16	24	22	42
	Cooler	0	0	0	0	84	74	78	58
PHV	Less humid	70.37	11.11	0	0	15	0	4	16
	No change	29.63	88.89	100	100	85	100	85	84
	More humid	0	0	0	0	0	0	11	0
PWV	Slower	83.33	35.56	4	30	0	0	0	0
	No change	16.67	64.44	96	70	0	13	7	33
	Faster	0	0	0	0	100	87	93	67
PSV	Stronger	98.15	73.33	54	98	0	0	0	0
	No change	1.85	26.67	44	2	55	100	22	76
	Weaker	0	0	2	0	45	0	78	24

and the highest percentage of votes for "acceptable" in summer was for Site D (78%). Overall, Sites B and C have very similar thermal comfort performance in winter, whereas Site D is the most comfortable landscape type in summer.

The results of the weather parameter preference vote (see Table 11) indicates that in terms of PTV, the highest percentage of votes for "no change" in winter is for Site C (54%), and the highest percentage of votes for "no change" in summer is for Site D (42%). In terms of PHV, the percentages of "no change" voting for Sites B (88.89%), C (100%), and D (100%) in winter are very similar. This finding again proves that urban residents in the HSCW region do not perceive RH considerably and vote "no change" in summer. The percentage of "no change" in summer is consistent with that in winter. In terms of PWV, Site C (96%) has the highest percentage of "no change" votes in winter, whereas all four sites have large votes of "faster" in summer. In terms of PSV, Site C (44%) has the highest percentage of "no change" votes in winter, and Site B (100%) has the highest percentage of "no change" votes in summer. We combine the results of meteorological parameter preferences and find that the site most adapted to the outdoor thermal environment in winter is Site C.

The results of the votes on weather parameter preferences reveal some phenomena of interest. In winter, Sit A preference votes resulted in significant uniformity. Most people prefer warm temperatures, slight humidity, fast wind speed, and strong solar radiation. However, completely opposite preference situations to other measurement sites, such as wind speed, emerged. The reason is that many middle-aged and older adults were gathered in the square (dance) and gymnastics in Site A. Reducing clothing during exercise is favorable under conditions with warm air and intense solar radiation. It is also favorable under conditions with slight humidity and fast wind speed class to evaporate sweat quickly. Therefore, the thermal preference of a person depends not only on the thermal environment to which he/she is exposed but also on the state of his or her activity.

4.3.3. *Analysis of thermal comfort indices*

Fig. 5 shows the hour-by-hour PET/UTCI variation for the four sites in winter and summer, which can be called the thermal comfort calendar, to visualize the thermal comfort variation at each measurement site. The graph shows that in winter, PET overestimates the body's thermal response, and the majority of the time is "extreme cold stress," which is obviously unscientific. Therefore, PET is not suitable for use in winter in

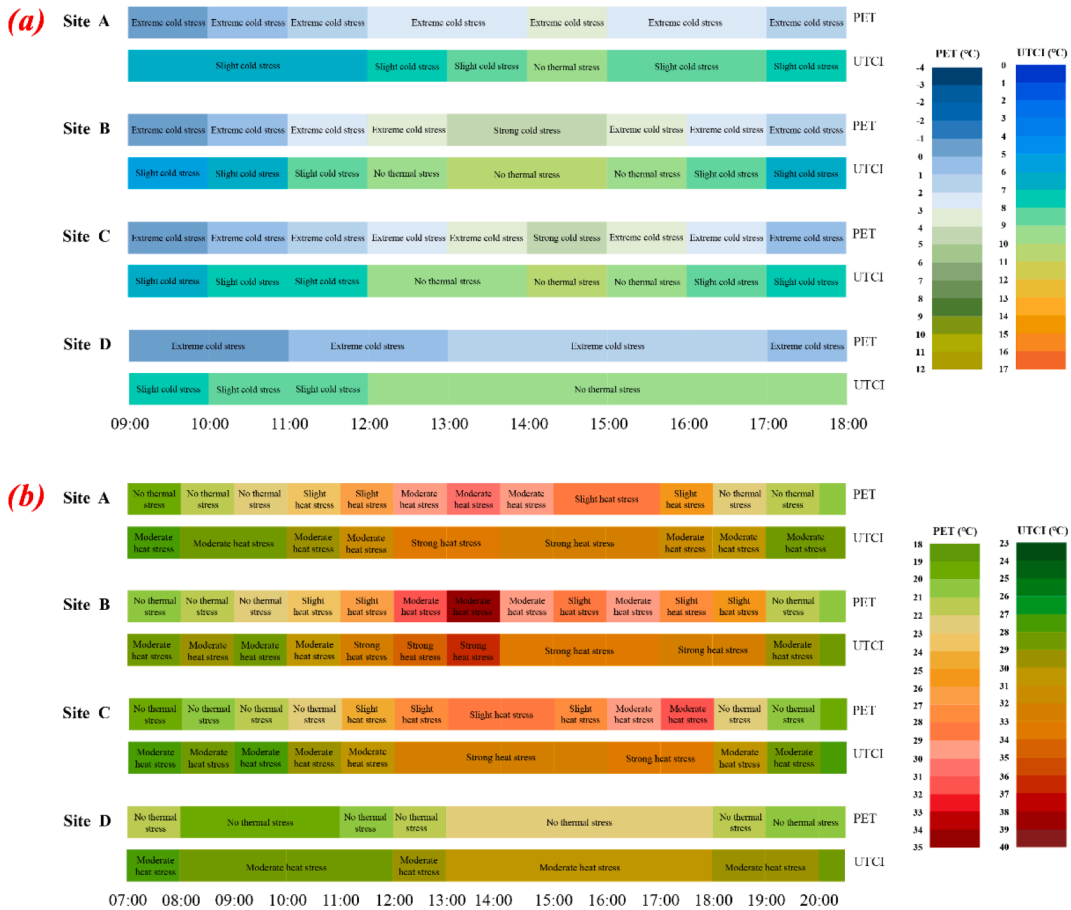

Fig. 5. Thermal stress performance of different landscape types during the field survey. (a) Winter, (b) Summer.

the HSCW region. The results of UTCI were applied, indicating that the thermal stresses of Sites B and C are "no thermal stress" from 12:00–16:00, and the thermal stresses of all four measurement points were "no thermal stress" from 14:00–15:00. In summer, the heat stress at the four measurement sites during 07:00–09:00 and that during 19:00–20:00 is "no thermal stress" (in PET) and "moderate heat stress" (in UTCI). Therefore, the most comfortable time to visit the park is 14:00–15:00 in winter and 07:00–09:00 and 19:00–20:00 in summer. The observed thermal stress distribution at the measurement sites indicates that the thermal comfort changes at Sites B and C are very similar.

The combination of meteorological parameters, subjective questionnaire, and thermal comfort index variation shows that Sites B and C are the most comfortable landscape types in winter. Site D is the most comfortable landscape type in summer. Different landscape types show differences in different seasons. Increasing solar radiation intensity in winter and increasing wind speed rate in summer are the uniform results formed by different measurement sites, which should become the future research focus for improving the OTC conditions.

4.4. Determination of thermal comfort benchmarks

4.4.1. T_n

PET and UTCI have become two important indicators for OTC

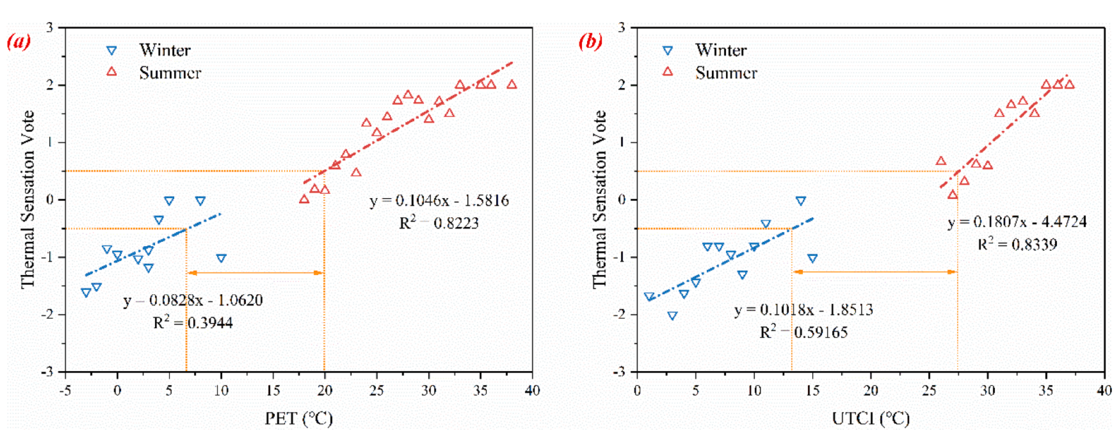

Fig. 6. Correlation between thermal comfort indices and mean TSV in winter and summer. (a) PET, (b) UTCI.

evaluation. However, their applicability in the HSCW region is unknown. Thus, we conducted a linear regression analysis of PET/UTCI and the mean TSV for each PET/UTCI degree interval. Also shown in Fig. 6, the models are as follows.

PET (see Fig. 6a):

$$\text{In winter}: \ y = 0.0828x - 1.0620 \ \left(R^2 = 0.3944\right) \tag{3}$$

$$\text{In summer}: \ y = 0.1046x - 1.5816 \ \left(R^2 = 0.8339\right) \tag{4}$$

UTCI (see Fig. 6b):

$$\text{In winter}: \ y = 0.1018x - 1.8513 \ \left(R^2 = 0.5917\right) \tag{5}$$

$$\text{In summer}: \ y = 0.1807x - 4.4725 \ \left(R^2 = 0.8223\right) \tag{6}$$

The slope represents the sensitivity of Y to X: the larger the slope is, the more sensitive Y is to X. The slope of the regression equation in winter is smaller than that in summer for both PET and UTCI, indicating that both PET and UTCI are more sensitive to summer than winter in the HSCW region. The correlation coefficient (R^2) represents the accuracy of PET/UTCI in predicting OTC in the HSCW region. The R^2 values of the regression equations for both PET and UTCI in summer are larger than those in winter, further suggesting that PET and UTCI are suitable for outdoor thermal environments in summer. In summer, the slope of PET (0.1046) is smaller than that of UTCI (0.1807). The R^2 of UTCI (0.8339) in summer is greater than that of PET (0.8223). This finding further indicates that UTCI is better for summer thermal comfort assessment in the HSCW region than PET.

When $Y = 0$ (Y = mean TSV), the value of X is T_n. In Eqs. (3)–(6), when $Y = 0$, the values of X are 12.83 °C (T_n of PET in winter), 15.12 °C (T_n of PET in summer), 18.18 °C (T_n of UTCI in winter), and 24.75 °C (T_n of UTCI in summer), respectively. The neutral temperature corresponds to the thermal stress of the thermal index (PET in Table 5 and UTCI in Table 6). 12.83 °C (moderate cold stress), 15.12 °C (slight cold stress), 18.18 °C (no thermal stress), 24.75 °C (no thermal stress).

4.4.2. NTR

NTR is the range of values of X for $Y = [-0.5, +0.5]$ on the basis of the neutral temperature regression equation (see Fig. 6). In Eqs. (3)–(6), when $Y = [-0.5, +0.5]$, the values of X are 6.79 °C, 19.90 °C, 13.27 °C, and 27.57 °C, respectively. For PET, the range was between 6.79 °C and 19.90 °C, spanning from the "strong cold stress" to the "no thermal stress" category (Table 5). Similarly, the NTR for UTCI (13.27 °C to 27.25 °C) has two levels on its scale, "no thermal stress" and "moderate heat stress" (Table 6).

4.4.3. TAR

TAR is defined as the temperature range that is acceptable to at least 80% of interviewees, i.e., at most 20% of interviewees consider this thermal comfort range to be unacceptable. For each 1 °C PET/UTCI interval, the unacceptable percentage is calculated, and a quadratic polynomial fit is performed. As shown in Fig. 7, the models are as follows.

$$\text{PET}: \ y = 0.2088x^2 - 5.1652x - 32.9744 \ \left(R^2 = 0.7693\right) \tag{7}$$

$$\text{UTCI}: \ y = 0.3489x^2 - 12.6687x + 98.9933 \ \left(R^2 = 0.7873\right) \tag{8}$$

ATR was calculated for 80% of the respondents and ranged from 2.8 °C to 21.9 °C for PET (Fig. 7a) and 8.1 °C to 28.3 °C for UTCI (Fig. 7b), both of which are wider than the NTR corresponding to the thermal index. (The neutral PET range is 6.79 °C to 19.90 °C, and the neutral UTCI range is 13.27 °C to 27.25 °C.) This finding indicates that urban residents in the HSCW region have a strong psychological adaptation to outdoor thermal environment changes. Therefore, conforming to local conditions in urban design/planning is necessary.

5. Discussion

5.1. Comparison of landscape spaces

We found from Section 3.3 that the most comfortable landscape types in winter are lakeside (Site B) and lawn (Site C), and the most comfortable landscape type in summer is woods (Site D). This finding indicates that a considerable difference exists in the influence of different landscape types on human thermal comfort. The effect of interviewees' activity status on thermal comfort may outweigh the effect of landscape type. Finally, the interviewees' expectations of the park are mainly focused on fast wind speeds in summer and strong radiation in winter. All these results provide important reference values for the construction of urban parks.

Xu et al. (2018) concluded that landscape type has a significant effect on human thermal comfort and that residents want strong solar radiation and high temperatures in winter but are insensitive to v or RH. Wang et al. (2018) showed that different urban green spaces present dramatic differences in the performance results on OTC. Previous studies also verified our findings that the human thermal comfort impact varies by landscape type. However, the preference for meteorological parameters differs among residents of each region, which is closely related to local meteorological conditions.

Two findings (The thermal comfort of the same landscape space is different in different seasons. The thermal comfort of different landscape spaces is different even in the same season.) were confirmed by Fang et al. (2019), Mi et al. (2020), Shang et al. (2020b), and Xu et al. (2019).

5.2. T_n

Table 12 shows the results of several OTC studies regarding T_n. The

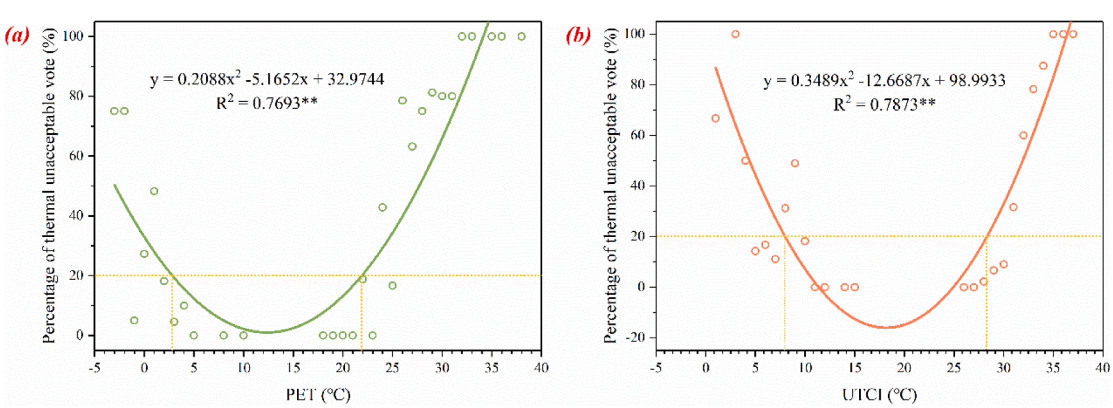

Fig. 7. Correlation between thermal comfort indices and thermal unacceptability votes. (a) PET, (b) UTCI (Note: ** Significance at the 1% level, two-tailed).

Table 12
T_n in different OTC studies.

City	Climatic region	Method	Function expression	T_n	Reference
Miangyang	HSCW	LR, MTSV vs PET (1 °C bin)	Winter: $y = 0.0948$ x - 2.2275 (R^2=0.815) Summer: $y = 0.0718$ x - 1.6383 (R^2=0.868)	Winter: 23.5 °C Summer: 22.8 °C	(Huang et al., 2019)
Chengdu	HSCW	LR, MTSV vs PET (1 °C bin)	$y = 0.105$ x - 2.6 (R^2=0.60)	Summer: 24.4 °C	(Zeng & Dong, 2015)
Haikou	HSWW	LR, MTSV vs PET (1 °C bin)	Spring: $y = 0.214$ x - 5.096 (R^2=0.803) Winter: $y = 0.389$ x - 7.463 (R^2=0.845)	Spring: 23.8 °C Winter: 19.2 °C	(Shang et al., 2020b)
Harbin	SC	LR, MTSV vs PET (1 °C bin)	$y = 0.1224$ x - 2.0527 (R^2 = 0.9738)	All year: 16.94 °C	(Yin et al., 2021)
Changsha	HSCW	LR, MTSV vs PET (1 °C bin)	$y = 0.168$ x - 4.686 (R^2=0.896)	Summer: 27.9 °C	(Yang et al., 2013)
Miangyang	HSCW	LR, MTSV vs PET (1 °C bin)	Summer: $y = 0.1114$ x - 3.0032 (R^2=0.868) Winter: $y = 0.0735$ x - 1.2726 (R^2=0.6097)	Summer: 27.0 °C, Winter is 17.3 °C	(Cheng et al., 2019)
Beijing, Xi'an, Hami	C	LR, MTSV vs UTCI (1 °C bin)	Beijing: $y = 0.0598$ x - 1.0179 (R^2=0.8068) Xi'an: $y = 0.0531$ x - 0.9196 (R^2=0.7973) Hami: $y = 0.1021$ x - 0.6562 (R^2=0.7184)	Beijing: 17.0 °C Xi'an: 17.3 °C Hami: 6.4 °C	(An et al., 2021)
Chengdu	C	LR, MTSV vs PET/ UTCI (1 °C bin)	PET: winter: $y = 0.0828$ x - 1.0620 (R^2 = 0.3944) summer: $y = 0.1046$ x - 1.5816 (R^2 = 0.8223) UTCI: winter: $y = 0.1018$ x - 1.8513 (R^2 = 0.5917) summer: $y = 0.1807$ x - 4.4725 (R^2 = 0.8223)	PET: winter: 12.83 ℃ summer: 15.12 ℃ UTCI: winter: 18.18 ℃ summer: 24.75 ℃	This study

Notice: LR is Linear Regression, MTSV is mean TSV.

present study was conducted in the HSCW region, but the neutral PET in summer was considerably different from the results of other studies belonging to the same climatic region. This considerable difference may be caused by measurement site selections. We found considerable differences among the studies conducted in the same city, with the results of Huang et al. for a neutral PET of 22.8 °C in summer and Cheng et al. for a neutral PET of 27.0 °C in summer. Both studies were conducted in Mianyang. However, a 4.2 °C difference exists in the neutral PET for the same season, which is already an order of magnitude difference in terms of thermal stress (22.8 °C: No thermal stress, 27.0 °C: Slight heat stress). This finding indicates that the thermal benchmark acquisition of OTC is considerably influenced by the meteorological parameters to the environment around the measurement site, i.e., microclimate is the most important factor in shaping OTC. Therefore, the one-to-one correspondence principle should be followed for the study of OTC, i.e., the data of the measurement point should be applied to the surrounding environment.

5.3. TAR

Table 13 shows the results of several OTC studies regarding TAR. The comparison of the 80% acceptable range with other studies indicates that TAR in Chengdu is narrower than that in Harbin, which is an SC region with very low temperatures. However, the reason for the wide TAR in Harbin may be the great psychological satisfaction that sunny days bring to people. This assumption suggests that the width of TAR in different climatic regions varies. TARs in Hong Kong, Taiwan, and Xi'an are relatively close. In climatic regions with smooth climate change (cold region and HSWW region), the human body may be slightly adaptable to extreme weather; thus, a consistent narrower TAR is exhibited. This statement suggests that TAR width may be consistent across climatic regions because of human adaptability. In conclusion, thermal acceptability and human adaptability are closely related because of the local climate.

5.4. Limitations of this study

This study applies a field research method combining objectively measured meteorological parameters and subjective questionnaires. The results of the study represent a typical study of OTC in Chengdu, an HSCW region of China. The method in this study can be extended to other climatic regions to obtain various thermal benchmarks for OTC in a specific region.

Despite many interesting results, this study still suffers from some research limitations: (1) We find that activity status affects the results of meteorological parameter preference voting but do not delve into the specific mechanism of activity status on human perception. (2) Most respondents are aged 45 years old or above because the field survey was conducted on weekdays. A wide age group should be involved to obtain comprehensive local thermal benchmark results. (3) OTC is considerably affected by the seasons. The study should be conducted in all four seasons to enable a comprehensive understanding of seasonal changes in OTC throughout the year. Our study was conducted only in winter and summer. (4) This study only focuses on natural landscape space and lacks consideration of artificial structures (e.g., pavilions and corridors). In the field survey, we found that many citizens would choose to stay inside artificial structures. (5) The study did not consider factors such as behavioral adaptation, thermal history, and response to the physical environment of urban park interviewees, which play an important role in gaining insight into the OTC of urban residents. (6) This study only focuses on a carefully selected park. Reasons for choosing this park have been attentively explained in Section 2. However, the transferability or generalizability of the exciting findings is still uncertain, which is a rooted critique for the case study research (Bao, Lee, & Lu, 2020; Bao, Lu, & Hao, 2021). Extending the analytical framework to more study areas (sampling more parks) is suggested for future studies to obtain

Table 13
TAR in different OTC studies.

City	Climatic region	Method	Function expression	TAR	ΔTAR	Ref.
Harbin	SC	QR, PTUV vs PET (80%)	$y = 0.0007\times^2–0.0226x+0.2976$ (R^2=0.8953)	5.14 –27.15 °C	22.01 °C	(Yin et al., 2021)
Harbin	SC	QR, PTUV vs UTCI (80%)	$y = 0.0005\times^2–0.0096x+0.1557$ (R^2=0.7027)	−3.8 - 23.0 °C	26.8 °C	(Zhu et al., 2020)
Hongkong	HSWW	LR, PTUV vs PET/UTCI (80%)	PET: y=−1.6587 x + 145.48 (R^2=0.4908) UTCI: y=−2.3625 x + 171.68 (R^2=0.7239)	21.3 - 39.5 °C (PET) 22.7 - 38.8 °C (UTCI)	18.2 °C 16.1 °C	(Cheung & Jim, 2018)
Xi'an	C	QR, PTUV vs UTCI (80%)	$y = 0.143\times^2–6.6036\ x + 92.223$ (R^2=0.8605)	18.0 - 29.1 °C	11.1 °C	(Xu et al., 2019)
Xi'an	C	QR, PTUV vs PET (80%)	$y = 0.0749\times^2–2.7592x+31.179$ (R^2=0.7603)	10.9 – 25.9 °C	15.0 °C	(Ma et al., 2021)
Taiwan	HSWW	QR, PTUV vs PET (80%)	$y = 0.0017\times^2$ - 0.0958x + 1.4856 (R^2 = 0.7673)	21.6 – 35.4 °C	13.8 °C	(Lin & Matzarakis, 2008)
Chengdu	HSWC	QR, PTUV vs PET (80%)	PET: $y = 0.2088\times^2–5.1652x-32.9744$ (R^2 = 0.7693) UTCI: $y = 0.3489\times^2–12.6687x+98.9933$ (R^2 = 0.7873)	2.8 – 21.9 °C (PET) 8.1 – 28.3 °C (UTCI)	19.1 °C 20.2 °C	In this study

Notice: QR is quadratic regression, PTUV is the percentage of unacceptable thermal votes, ΔTAR is the width of TAR.

more persuasive conclusions.

6. Conclusions

In this study, meteorological field measurements and subjective questionnaires were used to assess human thermal comfort using PET and UTCI, with the aim of exploring the differences in thermal comfort of different landscape types and determining the thermal benchmarks for OTC in Chengdu urban park. The main findings of this study are as follows:

(1) This study is the first to predict the relative importance of meteorological parameters on TSV through machine learning techniques. The results indicate that TSV is mainly predicted by RH and T_a in winter and by T_a in summer (accounting for more than 70% of importance). The thermal sensation is shaped by different factors in different seasons.
(2) In winter, the most comfortable types of landscape spaces are lakeside (Site B) and lawn (Site C). In summer, the most comfortable type of landscape space is woods (Site D). The thermal comfort performance of different landscape types considerably varies across the season. The majority of interviewees would like to increase solar radiation (winter) and wind speed (summer). The most comfortable time to visit the park is 14:00–15:00 in winter and 07:00–09:00 and 19:00–20:00 in summer.
(3) PET and UTCI show great variability during the evaluation of OTC in an HSCW region. UTCI is more accurate than PET in determining the neutral temperature. Moreover, PET and UTCI show considerable seasonal differences in application, with R^2 being much higher in summer than in winter in terms of central temperature. Therefore, using UTCI to determine the neutral temperature in summer in the HSCW region is recommended. However, their applicability in the HSCW regions in winter still needs further study.
(4) The urban park of Chengdu, located in the HSCW region, has neutral temperatures of 12.83 °C (PET) and 18.18 °C (UTCI) in winter and 15.12 °C (PET) and 24.75 °C (UTCI) in summer. The NTR is 6.79 - 19.90 °C (PET) and 13.27 - 27.25 °C (UTCI). The TAR (80%) is 2.8 - 21.9 °C (PET) and 8.1 - 28.3 °C (UTCI). Thermal benchmarks were obtained for the HSCW region.
(5) The thermal benchmarks for OTC show considerable variability regardless of whether the climatic regions are the same because OTC is considerably influenced by the meteorological parameters of the environment surrounding the measurement point, i.e., the microclimate is the most important factor affecting OTC. Therefore, OTC studies studiesshould be conducted extensively to explore its intrinsic uniformity.

Declaration of Competing Interest

This paper has no conflict of interest.

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