RESEARCH

USING PHYSIOLOGICAL DATA TO IMPROVE THE ACCURACY OF OUTDOOR THERMAL COMFORT EVALUATION FOR THE ELDERLY IN A HOT SUMMER AND COLD WINTER AREA OF CHINA

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ABSTRACT

Elderly people in regions of China with hot summers and cold winters have significantly higher heat sensitivity than people in other regions and are ambiguous in their subjective perceptions of temperature, humidity, and solar radiation. This makes the elderly more vulnerable to the heat; consequently, when they engage in outdoor activities during the summer wearing light clothing, their diminished thermal perception increases the risk of heat stress injuries. Therefore, to more accurately evaluate the outdoor thermal comfort perception of the elderly in summer, this study used traditional field meteorological measurements, a questionnaire survey, physiological data, and machine learning prediction methods, to establish an outdoor thermal benchmark for retirement communities in hot summer and cold winter regions. Findings from the study reveal that the neutral universal thermal climate index (NUTCI) and the neutral universal thermal climate index range are 25.94°C and 22.23°C to 29.66°C respectively, and that the thermal comfort threshold is 35.39°C. It was also found that for 80% of elderly residents in the two retirement communities studied, the thermal acceptable range is from 19.41°C to 35.07°C. Using these findings as a guide, the thermal categories proposed are neutral 22.23°C to 33.08°C, slightly warm 33.08°C to 39.68°C, warm 39.68°C to 43.52°C, and hot above 43.52°C, with a preferred UTCI of 27.02°C.

KEYWORDS

outdoor thermal comfort, elderly, physiological parameters, hot summer and cold winter region, machine learning, China

1. INTRODUCTION

With socio-economics and aging populations accelerating worldwide, taking care of the health and wellbeing of the elderly is a pressing concern in most countries (Jin et al., 2020) Studies have found that physical activity enhances memory, speeds up cognitive processing, and slows cognitive decline (Larson et al., 2006) and that older people can stay mentally healthy and happy through increased socialization (Lindsay-Smith et al., 2019). There is also evidence to

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suggest that an appropriate and suitable living environment is crucial for the independence and quality of life of the elderly in retirement communities (Rosenberg & Everitt, 2001), and that outdoor thermal environments can increase the frequency with which older adults participate in outdoor activities (Yao et al., 2022). Since for those in retirement communities, the area outside of their building serves as their primary outdoor activity space, significantly impacting their physical and mental health, improving and maintaining a comfortable outdoor thermal environment is key to improving their quality of life.

2. LITERATURE REVIEW

Outdoor activities of the elderly are closely related to features of the built environment: Lian et al. (2016) focused on the walking activities and spatial choices of Alzheimer's patients within elder care facilities and their courtyards; Huang and Wu (2015) quantified individual needs and travel characteristics of the elderly; Li et al. (2018) analyzed the interaction between behavior and environment in behavioral scenarios for elderly livable paths; Jiang et al. (2019) explored the impact of factors such as mixed land use patterns and convenient commercial service facilities on outdoor activities of the elderly; and Yuan and Chen (2022) considered the cognitive perspective by incorporating easily perceived meso-micro street environment variables into the design of age-friendly walking environments.

Built environment features can indirectly affect the thermal comfort of elderly outdoor activities by altering the microclimate, which greatly influences the outdoor environment and thereby the outdoor spatial activities (Chen & Ng, 2012). A comfortable microclimate can encourage outdoor activities and draw people to linger and participate, but when the discomfort level of the microclimate surpasses a specific threshold, these areas cease to host activities (Huang et al., 2016). The elderly's perception of the outdoor environment differs from the general population, being more sensitive to extreme temperatures, thus having special requirements for outdoor rest spaces from a microclimatic perspective. Elderly people are particularly susceptible to heatstroke or sunstroke in the sweltering outdoor conditions of summer, occasionally resulting in fatalities (Worfolk, 2000). Thermoregulation during outdoor activities involves multiple human body systems, including cardiovascular, respiratory, renal, and nervous systems, to adapt to varying thermal environments. However, this adaptive capacity can decline due to dysfunctions in the body temperature control process.

The physiological and psychological distinctions between older and younger individuals encompass a decline in basal metabolic rate (Salata et al., 2017), reduced sensitivity to temperature (Forcada et al., 2021), and decreased tolerance to heat and cold (Zhang et al., 2019). Elderly people show a diminished response to heat in warm environments, evidenced by delayed skin vasodilation and a decrease in maximum capacity (Rooke et al., 1994). As a result, the elderly's capacity to lose or gain heat in extreme temperatures is limited, potentially leading to excessively high or low core temperatures (Blatteis, 2011). Moreover, as age advances, alterations in the nervous system result in decreased thermal sensitivity and perception, especially a notable reduction in high temperature perception in the elderly (Guergova & Dufour, 2011). In regions with hot summers and cold winters, traditional living habits and social needs make it possible for a large number of outdoor activities to still exist in the summer for the elderly. The health risks associated with these outdoor activities for the elderly during summer have become a matter of considerable concern.

In the assessment of thermal conditions in various outdoor settings (Cheung & Jim, 2017; Shooshtarian & Ridley, 2016), the influence of a variety of factors is taken into account, including direct factors such as physical, physiological, and psychological; indirect factors such as social, personal, cultural, and thermal history (Jin et al., 2020); and physical factors centered on meteorological parameters (Tsitoura et al., 2014). Therefore, combining subjective evaluations with meteorological parameters, researchers have developed models for thermal comfort assessment, such as the Predicted Mean Vote (PMV) (Fanger, 1972), the Standard Effective Temperature (SET) (Gagge et al., 1986), the Physiologically Equivalent Temperature (PET) (Höppe, 1999), the Mean Radiant Temperature (MRT) (Chen et al., 2015), and the Universal Thermal Climate Index (UTCI) (Blazejczyk et al., 2012).

Earlier research primarily took place in urban public areas, with outdoor environments such as streets (Kim et al., 2023), parks (Wei et al., 2022), residential areas (Brozovsky et al., 2021), industrial zones (He et al., 2023), and university campuses (Salata et al., 2016). The elderly use these spaces less frequently than other groups, and thermal comfort studies of retirement communities or centers are mostly focused on the perception of indoor environments. For instance, (Zheng et al., 2022) conducted a study in a Xi'an nursing home and found that the elderly's thermal comfort perception has seasonal characteristics. (Sudarsanam & Kannamma, 2023) conducted surveys on the thermal comfort of the elderly at a home in India's warm and humid climates, showing that the elderly's thermal comfort range is narrower than that of younger people, and the neutral temperature for men is higher than for women. With the construction of age-friendly living environments in recent years, there has been an increase in the selection of professional elderly care facilities. The outdoor environment of retirement communities plays a crucial role in the lives of the elderly, being a vital part of outdoor open spaces. In contrast, fewer studies have focused on outdoor thermal comfort in retirement communities and most of them have used subjective questionnaires and meteorological parameter measurements to establish thermal benchmarks. Baquero Larriva and Higueras (2020) assessed the elderly's thermal perception in Madrid's urban outdoor spaces using PET and UTCI comparisons, and Yao et al. (2022) used PET to explore the outdoor thermal preferences of the elderly in the Qinghai-Tibet Plateau area.

In addition, research on in situ thermal comfort and influencing factors of the elderly population based on traditional thermal comfort modeling has begun to emerge, and the influencing mechanisms of different dimensional factors such as age, visual and acoustic sensations, and greenness have been investigated through statistical methods of data mining and updating. Zheng et al. (2023) used hierarchical clustering analysis to subdivide the elderly by age, finding that increased age affects sensitivity to temperature and humidity changes. Du et al. (2023) established a model for predicting outdoor thermal comfort for the elderly using binary logistic regression, incorporating visual and auditory perceptions. Fei et al. (2023) discussed the impact of green coverage in elderly care centers on comfort, based on the establishment of an outdoor thermal acceptance model. However, studies relating to thermal comfort assessment for the elderly often do not include physiological data, which may lead to significant discrepancies between subjectively assessed thermal perception levels in the elderly and the actual situation. Evaluating these levels using objective physiological data will help improve the accuracy of the assessments. Furthermore, research on thermal comfort in the outdoor environments of elder care communities during summer is also relatively scarce.

Utilizing a range of data collection methods such as questionnaire surveys, meteorological measurements, and physiological data collection, this study investigated thermal comfort in different architectural environments within retirement communities in regions with hot summers and cold winters, followed by an analysis using mathematical and statistical techniques. The following issues were investigated.

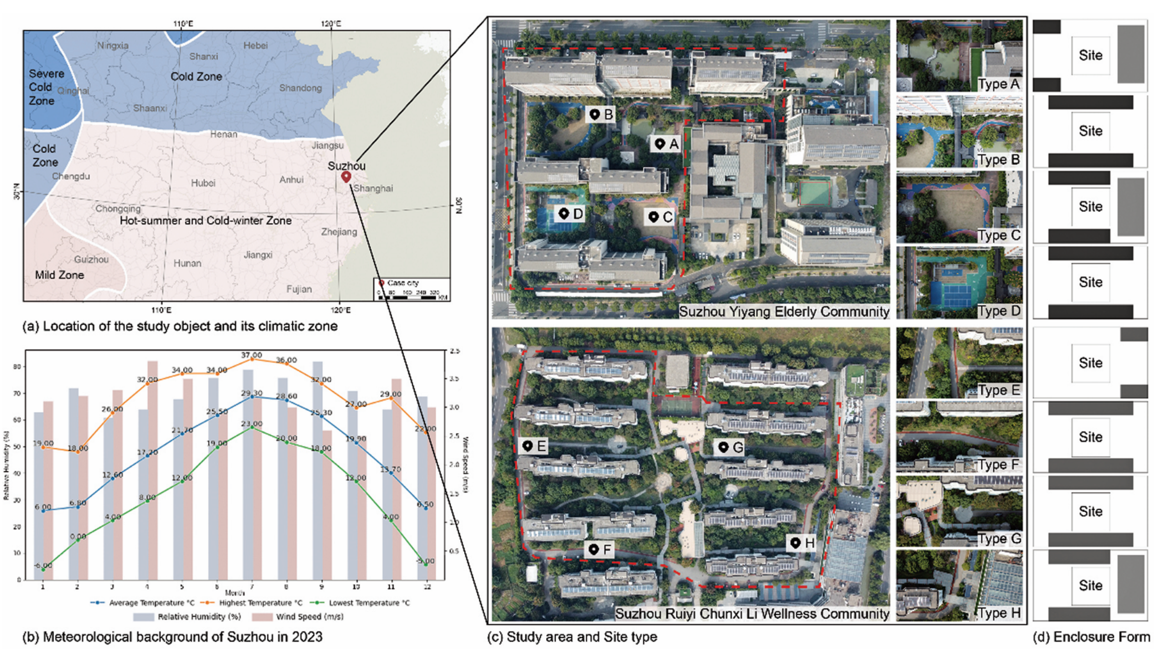
1. Variability in the selection of outdoor activity sites by elderly individuals in communities located in regions with hot summers and cold winters, and their thermal perceptions in various outdoor environmental features.
2. Using physiological data assistance and machine learning techniques to establish a subjective-objective combination of being as a path to improving the accuracy of thermal sensation voting in the elderly.
3. Adapting thermal benchmarks for outdoor spaces in retirement communities in regions with hot summers and cold winters, based on the predicted values of thermal sensation votes and thermal comfort index.

3. MATERIALS AND METHODS

3.1 Study area

The thermal environment problem is especially prominent in summer in the hot summer and cold winter regions of China, where summer is the peak period of outdoor activities for the elderly. The city of Suzhou, located in the central Yangtze River Delta and the southeast of Jiangsu Province (120°37′E, 31°19′N), was selected for this study as it has a typical Humid Subtropical Climate (Cfa) according to the Köppen Climate Classification System (2019), which means it is warm, humid, and rainy, with four distinct seasons, making it one of the most livable cities in the country. According to the climate zoning of the "Civil Building Thermal Engineering Design Standards," Suzhou falls under the hot summer and cold winter region, as shown in Figure 1(a), necessitating summer heat prevention and appropriate consideration for winter insulation. Figure 1(b) shows that the hottest months are July and August, and the coldest month is January.

FIGURE 1. Climatic background and site type of the study area.



This study focuses on two retirement communities in Suzhou's Huqiu district, a high-density residential area, and a low-density residential area, both of which are typical types of built-up retirement communities. The main reason for choosing these two retirement communities is the abundance of different types of outdoor environments within the communities that attract many elderly people to spend time outdoors for activities and relaxation. Based on characteristics such as enclosure forms, paving materials, greenness, and facility arrangements, outdoor spaces can be divided into eight types, as shown in Table 1. The greenness is defined

TABLE 1. Breakdown of site types

Type	Community	Enclosure Form	Paving Materials and Colors	Primary Vegetation Types	Vegetation Density	Facility Arrangements
A (Waterfront Leisure Space)	High-density residential area	Unidirectional enclosure with auxiliary buildings	Dark wood	Trees and shrubs	Sparse	Resting seats and tables
B (Trail Space)	High-density residential area	Bidirectional enclosure with high-rise apartments	Light plastic	Trees and shrubs	Dense	No facilities
C (Leisure Space)	High-density residential area	Tridirectional enclosure with high-rise apartments and auxiliary buildings	Light plastic and dark tile mix	Trees and lawn	Sparse	Several long benches
D (Exercise Space)	High-density residential area	Bidirectional enclosure with high-rise apartments	Light plastic	Trees and shrubs	Sparse	Resting benches and fitness equipment
E (Trail Space)	Low-density residential area	No enclosure	Light plastic	Trees and shrubs	Dense	Several resting seats
F (Main Road Space)	Low-density residential area	Bidirectional enclosure with low-rise apartments	Light plastic and dark asphalt concrete mix	Trees and shrubs	Sparse	No facilities
G (Courtyard Space)	Low-density residential area	Bidirectional enclosure with low-rise apartments	Dark Tiles	Trees and shrubs	Dense	Resting and exercise facilities
H (Leisure Space)	Low-density residential area	Tridirectional enclosure with low-rise apartments and auxiliary buildings	Light plastic and dark asphalt concrete mix	Trees and shrubs	Sparse	Several resting seats and tables

by describing the primary vegetation types and vegetation density. Detailed depictions of the actual site features of these spaces are provided in Figure 1(c).

3.2 Respondents

The study involved a total of 360 elderly people from both retirement communities, all residing in apartments and regularly participating in outdoor activities, making them capable of objectively evaluating the outdoor environment. As per the World Health Organization's guidance, an ideal sample size for a group should be approximately 400, making the sample size of this study acceptable (Johansson et al., 2014). The outdoor survey was conducted during the hottest season in Suzhou, which was from July 21 to August 4. To minimize the impact of humidity, surveys were carried out on days following rain-free weather during this period. Based on the understanding of the elderly outdoor time with the staff, the measurement time was set from 07:00 to 18:00 each day.

The 360 valid questionnaires collected were categorized into 8 groups, A-H, based on the type of outdoor site elderly respondents occupied. Participants' ages ranged from 59 to 96 years, with the average age approximately 80 years, notably higher in groups A and D at 86 years. The standard deviation of age in groups B and C was over 10, indicating a wider age distribution in these two groups. Height data revealed that except for group E, with an average height of 170.3 cm, other groups had an average height of about 163 cm. The standard deviation in height was generally about 7 cm, indicative of potential height differences between genders. Weight ranged from 39 to 90 kg. With the average weight in group G being lower at 53.6 kg, other groups had an average weight of about 58 kg, with a significant standard deviation, indicating notable weight differences. Clothing thermal resistance ranged from 0.2 to 0.6 Clo, with an average of 0.3 or 0.4 Clo and a standard deviation of about 0.1 Clo, indicating a relative uniformity in the clothing of the elderly across groups. Activity thermal resistance varied from 38.6 to 185.3 W/m^2, with an average of 105.1 W/m^2 in group G and 68.3 W/m^2 in group H; other groups averaged about 80 W/m^2, with a large standard deviation, particularly in groups B, C, and G, indicating significant activity variation in these groups.

3.3 Questionnaire survey

The questionnaire is divided into three parts: basic personal details of participants, thermal comfort survey, and thermal adaptive behavior and health status. Table 2 provides details of the questionnaire, while Figure 2(a) illustrates how it was administered. The collected data on clothing and activity thermal resistances were converted to numerical values based on the following established standards. The clothing thermal resistance values for elderly respondents were determined based on ASHRAE55 and ISO7730 standards (Turner et al., 2010). The activity thermal resistance was set based on activity types (W/m^2) and adjusted resting metabolic rates for the elderly were used to estimate activity thermal resistance, with 1 met for males being 43.10 W/m^2 and for females, 38.57 W/m^2 (Lührmann et al., 2002; Schellen et al., 2010).

3.4 Micrometeorological measurements

The meteorological parameters were collected simultaneously as shown in Figure 2(b). Measurement heights were determined by human core dimensions: 1.1 meters for standing subjects and 0.6 meters for those seated, following the ISO 7726 standards. Due to the frequent height adjustments required for mobile measurements in this study, tripods were used to stabilize the equipment, ensuring consistent collection heights for all devices. Equipment

TABLE 2. Questionnaire content

Basic personal details of participants	Thermal comfort survey	Thermal adaptive behavior and health status
Sex: male, female	Thermal sensation vote: neutral (0), slightly warm (1), warm (2), hot (3)	Behavior: moving to building shadows, wearing umbrellas, wearing hats, reducing clothing, drinking water
Age	Thermal comfort vote: uncomfortable (–1), neutral (0), comfortable (1)	Diabetes status: no (0), yes (1)
Height	Thermal acceptable vote: unacceptable (–1), acceptable (1)	Cardiovascular disease: no (0), mild (1), moderate and above (2)
Weight	Thermal preference air temperature: cooler (–1), no change (0), warmer (1)	Respiratory disease: no (0). mild (1)
Clothing	Thermal preference relative humidity: Drier (–1), no change (0), wetter (1)	
Activity in the last 20 minutes	Thermal preference air velocity: lowe r (–1), no change (0), higher (1)	
	Thermal preference solar radiation: weaker (–1), no change (0), stronger (1)	

measuring meteorological parameters was positioned within 3 meters of the respondents (Xi et al., 2012). Table 3 provides details of the devices used to measure meteorological and physiological parameters in the field, all of which underwent testing and calibration before being used. Specifically for the thermo-hygrometer, two devices were set up, and the average of the two data sets was taken to enhance measurement accuracy.

Three meteorological parameter measurements were conducted in each interview, using the average of the three as the final data. In thermal comfort research, mean radiant temperature is a key indicator, and its calculation is based on known data. Air velocity data is not used directly in processing because thermal comfort is influenced not only by air velocity but also by its rate of change (Oliveira & Andrade, 2007). The maximum air velocity recorded during each interview was integrated with the variation rate of air velocity, accounting for the standard deviation from three observations.

3.5 Physiological data collection

Physiological data were collected as shown in Figure 2(c). Drawing on research from neuroscience, psychology, and medicine, various physiological indicators have been found to effectively support traditional studies of psychological perceptions that mainly rely on questionnaires (Pan et al., 2012). Considering the potential difficulties and participants' reluctance in using physiological parameter collection devices outdoors, this study opted for a user-friendly and portable finger clip pulse oximeter. This device can measure the participant's percutaneous arterial oxygen saturation (SpO2), pulse rate (PR), and perfusion index (PI). During thermoregulatory sweating in humans, blood oxygen saturation can be altered due to the increased density and viscosity of the blood (Baker, 2019). Furthermore, to facilitate the dissipation of heat, the workload on

FIGURE 2. Content of field investigation.

the heart is elevated, manifesting as an increase in PR (Edholm et al., 1962). Concurrently, vasodilation occurs, thereby increasing blood flow and causing variations in the PI (Salloum et al., 2007). SpO2 has a high correlation with arterial oxygen saturation (SaO2), with similar values and the added advantage of easier measurement (Aoyagi & Miyasaka, 2002). Hence, this study uses SpO2 as an alternative indicator for SaO2.

3.6 Thermal comfort index

The study integrated an analysis of personal and meteorological factors, correlating these with TSV, and pinpointed factors with significant correlation. In instances of high correlation among

TABLE 3. Devices used to measure meteorological and physiological parameters

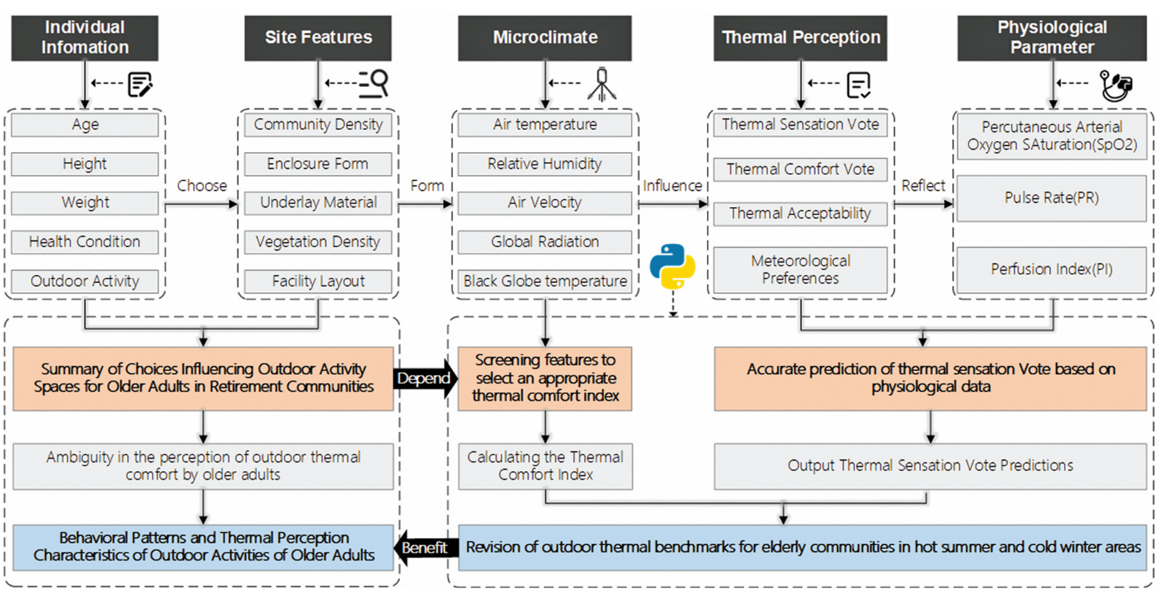
Instrument	Measured parameter	Measurement	Accuracy
Thermohydrometer (Testo 147H)	Air temperature (Ta)	–20–70°C	±0.5°C
	Relative Humidity (RH)	0–100%	±3%
Anemometer (Testo 405-V1)	Air velocity (Va)	0–10 m/s	±0.1 m/s
Black sphere thermometer (AZ 8778)	Black globe temperature (Tg)	0–80°C	±1.5°C
Solar power meter (Sanpometer SM206)	Global radiation (G)	0–3999 W/m^2	±10 W/m^2
Pulse Oximeter (Contec CMS50-Pro)	Percutaneous arterial oxygen saturation (SpO2)	35–99%	±1%
	Pulse rate (PR)	30–240 bpm	±1 bpm
	Perfusion index (PI)	0–20%	±1%

independent variables, addressing collinearity is essential to augment the explanatory capacity of the model (Eliasson et al., 2007). To calculate the thermal comfort index, the Python package Pythermalcomfort developed by Professor Tartarini from the University of California, Berkeley was chosen (Tartarini & Schiavon, 2020).

3.7 Statistical analysis

Figure 3 illustrates the study's two approaches to data analysis: traditional mathematical-statistical analysis, and machine learning. Descriptive statistics and data visualization techniques were

FIGURE 3. Data collection and analysis paths.



used to organize and analyze the collected data. Machine learning methods were used to explore the relationship between physiological data and thermal sensation, and to predict the outcomes of thermal sensation voting. Polynomial regression, which involves regression fitting using mathematical expressions with different coefficient variables (Cheng & Schneeweiss, 1998), was used in conjunction with the Lightgbm algorithm, the latter being advantageous for residual modeling, data classification accuracy, and processing time (Ke et al., 2017). Collinearity issues were addressed through correlation and variance inflation factor analysis, and features closely related to thermal sensation were selected (Marquardt, 1980), thus determining the appropriate thermal comfort index. Ultimately, mathematical-statistical methods, including linear regression fitting and logistic regression fitting, were used to establish benchmarks for thermal comfort (Kántor et al., 2012).

4. RESULTS

4.1 Thermal comfort status investigations

4.1.1 Objective meteorological measurements for thermal comfort

This study recorded meteorological parameters within a 3-meter radius of the elderly as shown in Table 4, including air temperature (Ta), relative humidity (RH), air velocity (Va), globe temperature (Tg), and global radiation (G). Groups G and H having the highest average temperature of 32.8°C, and group E the lowest average temperature of 31°C, with all temperature standard deviations below 2.4°C. Relative humidity varied widely, with group A, located in a waterfront space, having the highest average humidity of 73.6%, and group H the lowest at 63.6%. There was little variation in air velocity. Groups D and E experiencing lower speeds of 0.1 to 0.2 m/s. Global radiation fluctuated considerably, with group C having the highest average at 231.1 W/m^2. Average globe temperature was slightly higher than the air temperature, between 32°C and 34.4°C. Group C had the largest standard deviation of 3.7°C, while groups D, E, and H were lower with 1.3°C. Overall, there were significant differences in meteorological parameters between groups, reflecting the microclimatic characteristics of different spatial types.

TABLE 4. Meteorological data measurements

	Ta				RH				Va				G				Tg			
Type	max	min	mean	std	max	min	mean	std	max	min	mean	std	max	min	mean	std	max	min	mean	std
A	33.2	29.2	31.4	1.8	82.6	66.7	73.6	7.1	1.0	0.1	0.4	0.3	253.6	0.6	60.4	97.9	35.7	28.9	32.0	2.5
B	34.4	29.9	31.8	1.1	80.4	63.0	70.4	5.3	0.9	0.1	0.4	0.3	563.0	0.4	69.2	149.7	42.1	30.5	32.7	2.9
C	34.5	30.4	32.0	1.5	79.2	64.5	72.8	5.3	0.9	0.2	0.5	0.3	607.0	17.6	231.1	229.3	41.7	31.1	34.3	3.7
D	31.9	31.6	31.7	0.2	71.0	67.8	69.0	1.5	0.3	0.1	0.2	0.1	43.0	17.4	32.3	10.7	31.9	31.4	31.6	0.2
E	32.0	30.1	31.0	1.0	75.0	59.8	69.2	8.2	0.2	0.1	0.1	0.1	116.3	15.8	82.1	57.4	32.8	31.7	32.3	0.6
F	38.1	29.9	32.2	2.4	77.8	49.3	68.8	8.3	0.6	0.1	0.3	0.2	199.7	13.5	66.5	67.9	38.7	31.2	33.0	2.5
G	36.6	27.7	32.8	2.3	81.4	53.0	66.5	7.3	1.1	0.0	0.3	0.3	379.0	11.6	117.0	111.7	38.2	29.1	34.4	3.1
H	36.5	30.8	32.8	1.5	71.5	46.9	63.6	7.0	1.0	0.0	0.3	0.2	145.3	16.4	79.8	40.8	36.5	31.7	33.4	1.3

4.1.2 Subjective questionnaire surveys for thermal comfort

The results of the outdoor thermal sensation voting reveal the elderly's subjective responses to cold and hot conditions. Figure 4(a) indicates that "neutral" and "slightly warm" have the highest proportions in all groups, with groups B, C, and D having the highest percentage of "neutral," while groups A and E have the most "slightly warm." The thermal sensation voting in groups F, G, and H is more balanced, while in groups other than A and B, about 20% of respondents felt "hot." The thermal comfort voting results in Figure 4(b) show that "neutral" has the highest proportion, especially in locations A, B, and F. In groups A, B, C, and D, the proportion of "comfortable" is higher than "uncomfortable," while the opposite is true for groups E, F, G, and H. The thermal acceptable voting in Figure 4(c) reveals that in most groups, the proportion of "acceptable" exceeds "unacceptable," especially in groups B, D, E, F, and H. In groups A, C, and G, "unacceptable" does not exceed 40%. Overall, there is no significant difference in the elderly's subjective perception of the outdoor thermal environment among the different groups.

Figure 4(d) illustrates the thermal preferences of the elderly surveyed in the various groups. Regarding air temperature (Ta), more than 60% of respondents in each group preferred a lower temperature, especially in groups A, C, D, and G, where it reached 90%. In groups B, E, F, and H, about 20% thought the current temperature was suitable. For relative humidity (RH), around 60% or more in most groups preferred a reduction in humidity, while about 70% in groups C, D, and E found the current humidity suitable. Concerning air velocity (Va), most respondents in all groups found the current air velocity appropriate, but about 30% felt it could be stronger, with around 65% in group G preferring a stronger wind. Regarding solar radiation, approximately 60% of participants in groups A, C, and G wished for reduced solar exposure, while around 60% in the other groups found the current level suitable. Generally, the variations in thermal preferences among the elderly in different groups are not significant.

4.1.3 Physiological feedback of thermal comfort

This study objectively reflects the thermal perception of the elderly in different types of spaces by collecting physiological parameters. Table 5 displays the results for percutaneous arterial oxygen saturation (SpO2), pulse rate (PR), and Perfusion Index (PI). For SpO2, the maximum value reached 99.0%, with the lowest minimum values in groups B and H (88.0%), and the highest in group D (95.0%). The average SpO2 was highest in group D (96.8%) and lowest in group C (95.0%). For pulse rate, group E recorded the highest maximum and average values (130.0 and 103.3), and group H had the lowest average (79.6). Group D had the largest standard deviation in pulse rate (33.5), indicating the greatest variability. Regarding PI, the highest maximum value was in group F (15.6), and the lowest minimums were in groups F and H (0.5 and 0.4). The average PI was highest in group D (6.8) and lowest in group C (3.4). Group B exhibited the largest fluctuation in PI with a standard deviation of 4.5, while group C had the smallest fluctuation at 2.2.

4.2 Accurate thermal sensation voting prediction (TSVp) aided by physiological data

4.2.1 Physiological data characteristics

Considering that TSV is an ordinal categorical variable, this study paid special attention to its categorical characteristics during data processing. Based on the box plots in Figure 5(a), outliers in the dataset were addressed by removing 83 values that were out of range, to reduce data

FIGURE 4. Results of the weather preference survey.

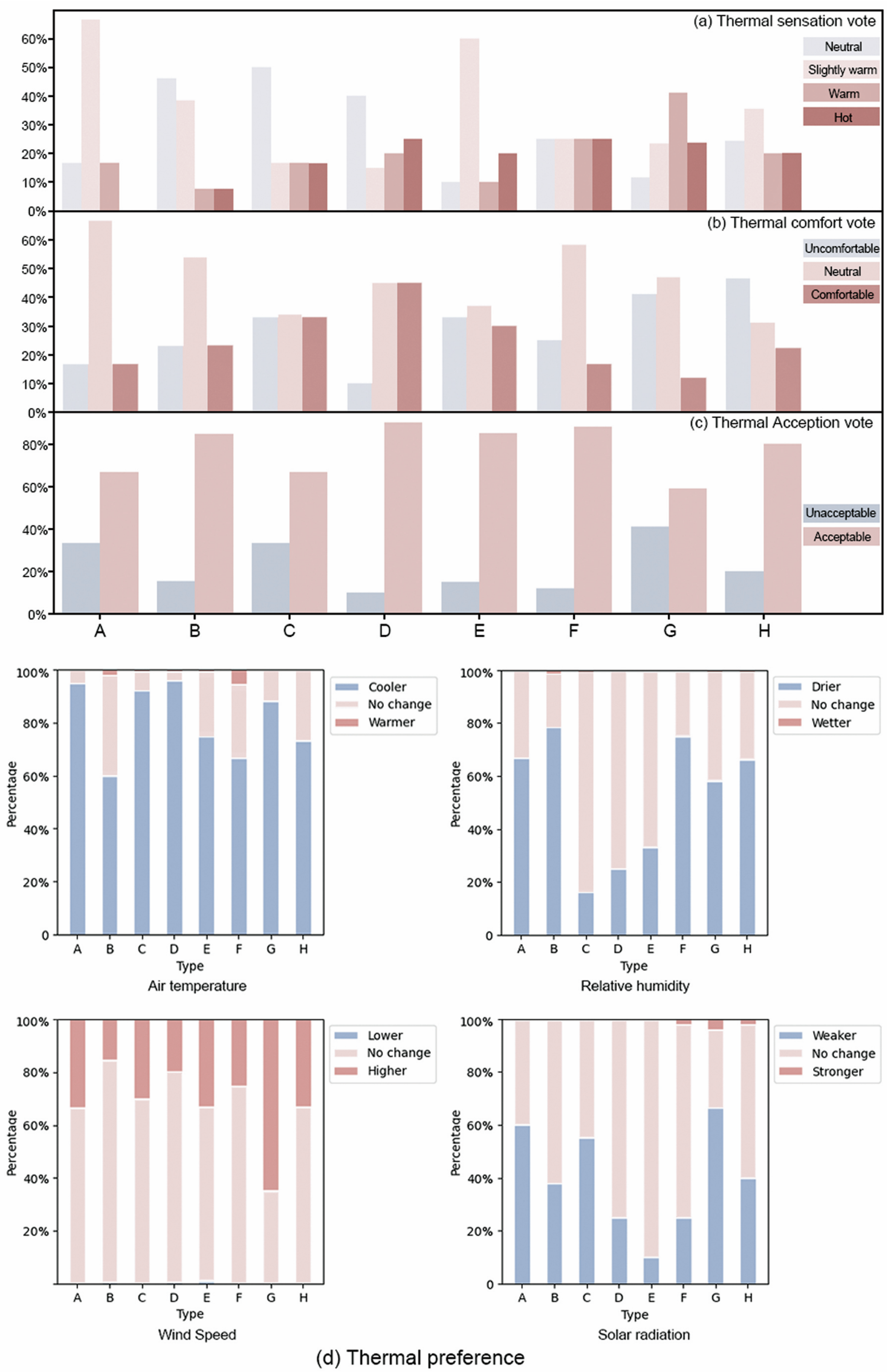


TABLE 5. Results of physiological data collection

Type	SpO2				PR				PI			
	max	min	mean	std	max	min	mean	std	max	min	mean	std
A	97.0	91.0	95.2	2.3	96.0	81.0	88.7	6.8	10.2	1.7	4.7	3.1
B	99.0	88.0	96.3	3.0	95.0	73.0	78.6	21.8	14.5	1.0	7.5	4.5
C	97.0	93.0	95.0	1.8	122.0	69.0	85.5	19.5	6.2	1.2	3.4	2.2
D	99.0	95.0	96.8	1.7	82.0	68.0	76.0	33.5	12.3	3.0	6.8	4.5
E	97.0	94.0	95.7	1.5	130.0	72.0	103.3	29.3	4.0	1.3	2.9	1.4
F	99.0	89.0	95.8	2.8	116.0	67.0	82.6	16.3	15.6	0.5	4.4	3.9
G	99.0	92.0	97.1	1.8	110.0	58.0	84.4	14.5	12.4	1.4	4.9	2.9
H	99.0	88.0	96.7	2.5	100.0	59.0	79.6	10.4	13.8	0.4	4.6	3.0

noise and increase stability. And the data of the sample of 20 respondents who had previously performed a greater amount of exercise was screened out. Violin plots in Figure 5(c) analysis revealed that the distribution range of SpO2 was between 96% and 100%, indicating that most samples were within normal levels. PR values fluctuated significantly across different TSV groups, reflecting variations in physiological responses. PI analysis showed that most values were concentrated around 0. Figure 5(d) explores the distribution and interrelationships of four physiological parameters: TSV, SpO2, PR, and PI. SpO2 is mostly concentrated in the medium-to-high value range, while PR is more evenly distributed, primarily in the medium range. PI data tends to be in the medium-to-low value range. Bivariate scatter plots show no clear clustering trend between TSV and other parameters, but there are indications of clustering in the low-value range for PR and PI. When TSV increases, SpO2 decreases. For PR and PI, female PI values cluster with increasing PR. The heat matrix shown in Figure 5(b) is the result of the correlation analysis. The correlation coefficient between TSV and SpO2 is –0.83, meaning that as TSV increases, SpO2 decreases, reflecting the physiological link between increased thermal sensation and reduced oxygen saturation. The correlation coefficient between TSV and PI is 0.58, indicating a moderate positive correlation. A correlation coefficient of –0.52 between SpO2 and PI suggests there may be an interaction or a common physiological mechanism between them. In contrast, PR shows weaker correlations with other parameters, indicating that PR is not a key parameter in this dataset. Overall, the strong correlation between TSV and SpO2 makes them a priority in research feature selection, while PI may also provide important information about physiological responses.

4.2.2 Machine learning models

Since scatter plots indicate a non-linear relationship between thermal sensation and physiological indices, this study adopted a polynomial fitting model. Utilizing Principal Component Analysis is (PCA), a novel Composite Physiological Index (CPI) was established, and its relationship with TSV was examined, yielding the formula: $TSV = -0.0058CPI^3 + 0.0099CPI^2 + 0.3657CPI + 1.3291$. Figure 6(a) shows that at lower TSV values, the predicted values are greater than the actual values, but this difference diminishes as TSV increases. Additionally, the

FIGURE 5. Box diagrams and Violin plots of physiological data for each category.

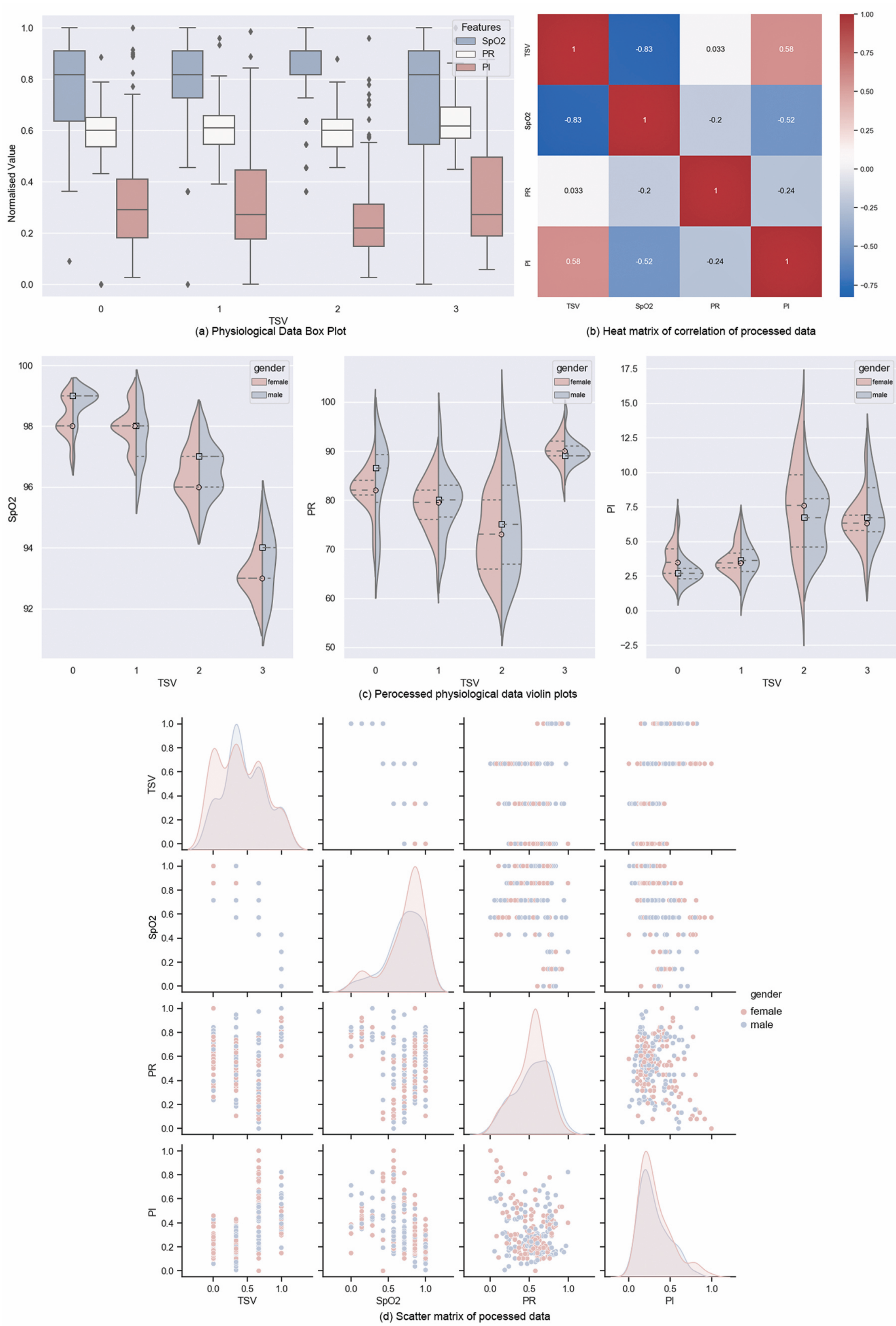
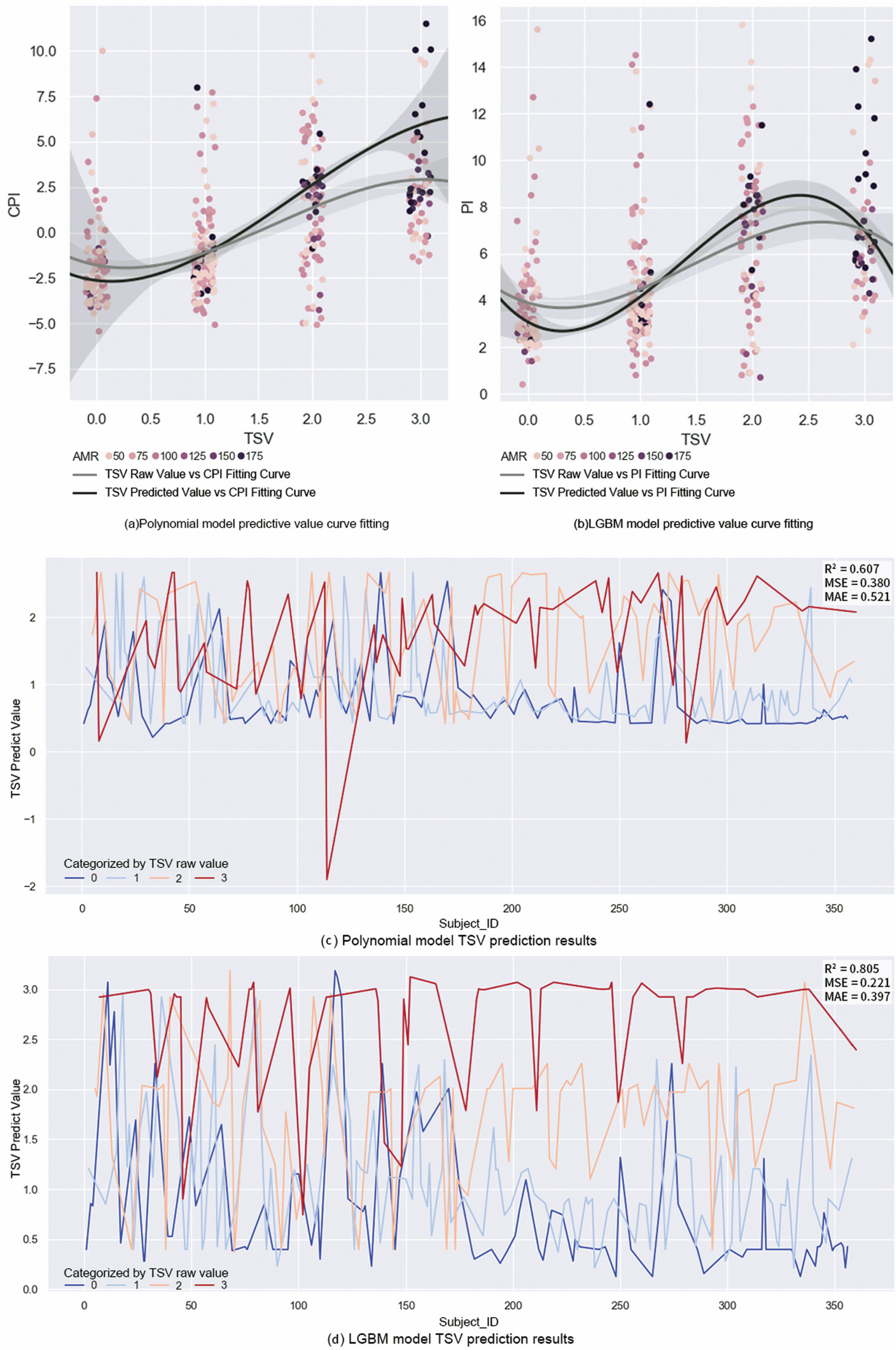


FIGURE 6. Machine learning model performance comparisons.



study found that with an increase in physical activity, both thermal sensation and CPI show an upward trend.

The scatter matrix plot of the data reveals a non-linear and intricate relationship between SpO2 and PI. The study utilized a gradient boosting tree-based Lightgbm model for predicting TSV, a model well-suited for managing ordinal categorical variables, improving generalization and minimizing overfitting. With TSV as the dependent variable, and SpO2 and PI as independent variables, the analysis was conducted in a machine learning process with 100 iterations. The dataset was divided into training and testing sets, used for learning and evaluating the relationship between SpO2, PI, and TSV. Figure 6(b) analysis of TSV actual and predicted values versus PI reveals that for TSV below 1.2, actual PI values exceed predicted ones; this inverts for TSV above 1.2, particularly near TSV = 2.4, where the discrepancy decreases and vanishes at TSV = 3.

4.2.3 Comparison of models

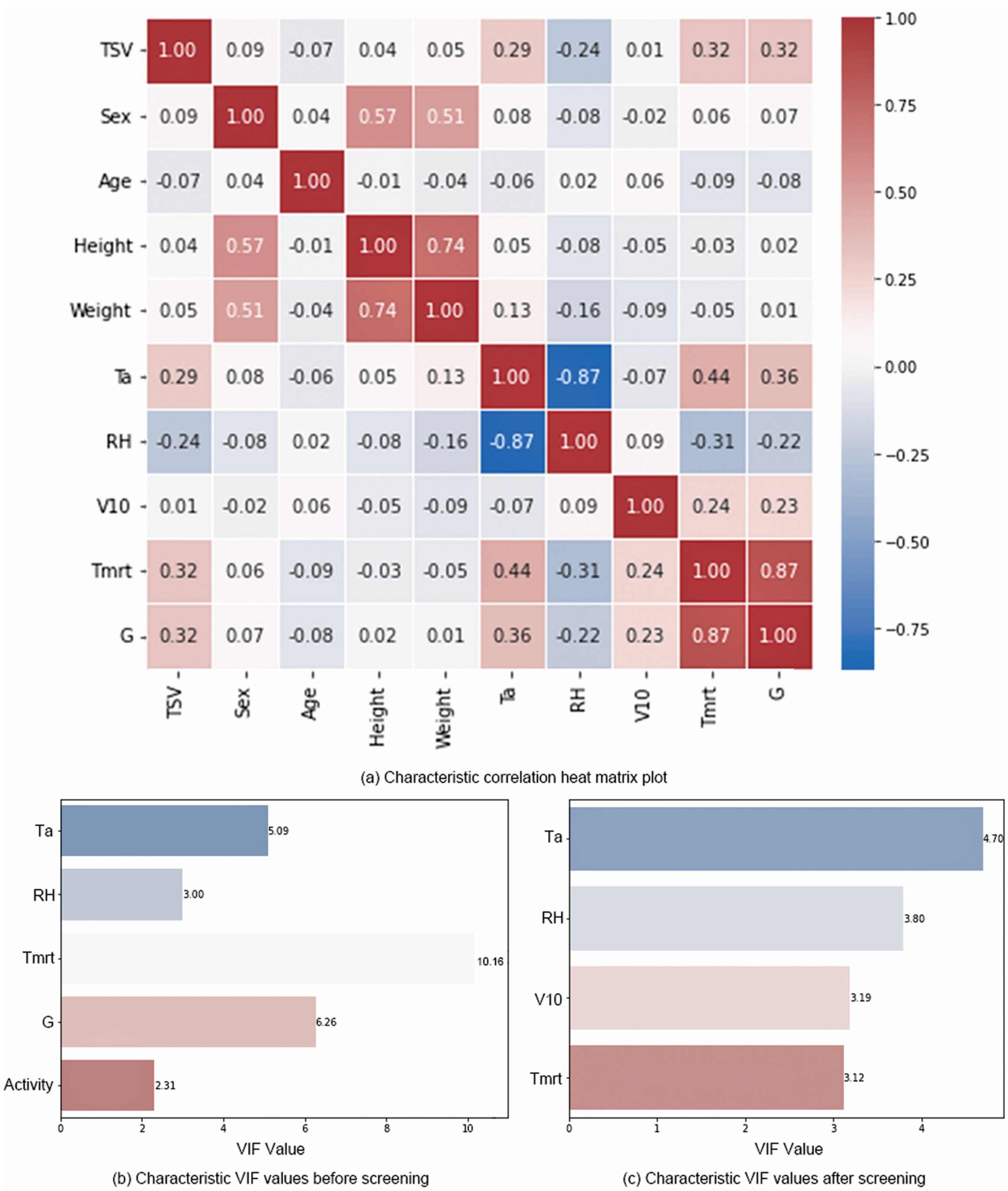
Lightgbm's determination coefficient (R^2) of 0.805 surpasses the polynomial fitting model's 0.607, signifying greater efficacy of Lightgbm in elucidating the variability of the target variable. Additionally, Lightgbm's Mean Squared Error (MSE) at 0.221 is below the polynomial fitting's 0.380, demonstrating its superior predictive accuracy. Lightgbm also exhibits a lower Mean Absolute Error (MAE) of 0.397, compared to 0.521 for polynomial fitting, further attesting to Lightgbm's superiority. Lightgbm more effectively captures the influence of SpO2 and PI on TSV, deals with non-linear relationships, and has mechanisms to prevent overfitting. Figure 6(c) and Figure 6(d) shows that Lightgbm is more stable than polynomial fitting when dealing with fluctuating data, which is crucial for enhancing the model's generalizability.

4.3 Selection and Calculation of appropriate thermal comfort index

Correlation analysis was performed on every feature in the data table. The heatmap Figure 7(a) reveals that TSV-related features encompass Ta, RH, Tmrt, and G. In particular, the correlations of Ta with RH and Tmrt with G are over 0.8. To further filter these features, the Variance Inflation Factor (VIF) was calculated to determine the presence of collinearity. Figure 7(b) indicates that the VIFs for Ta and G ranged from 5 to 10, whereas Tmrt's VIF surpassed 10. Tmrt, calculated from various numbers, inherently possesses higher collinearity. Ta and RH, as objectively gathered data, are influenced in the computation of Tmrt, resulting in an elevated VIF. Likewise, despite Tmrt being computed and G objectively collected, their correlation is significant. Indeed, elevated global radiation correlates with high mean radiant temperatures, but these high mean radiant temperature values are not solely impacted by shortwave radiation. Considering the significance of air temperature for outdoor thermal comfort and the study's emphasis on group rather than individual differences, personal parameters and global radiation were omitted from feature consideration. Figure 7(c) indicates that all remaining variables have a VIF less than 5, showing favorable outcomes. Based on feature screening results, for the outdoor thermal comfort evaluation in this study, UTCI was selected as the evaluation index, given the high correlation among meteorological parameters and the collective nature of the study subjects.

Calculation of the Universal Thermal Climate Index (UTCI) was conducted based on the filtered features, air temperature, relative humidity, air velocity, and mean radiant temperature. The results indicate that the mean UTCI is 36.42, standard deviation 2.55, minimum value 32.00, 25th percentile 34.90, median 36.00, 75th percentile 36.90, and maximum value 45.30.

FIGURE 7. Correlation and covariance analysis of multidimensional features.



4.4 *Thermal benchmark*

A total of 360 sample data were gathered in this study. Since TSVp is a predicted value derived from TSV and physiological data, its numerical noise is smaller than that of the original data. As the scale of data binning increases, the distortion of the original data also increases; therefore, to enhance fitting performance, data was binned at every 0.5° UTCI value. The mean TSVp, mean thermal sensation MTSVp, and mean UTCI within each sub-case group were also obtained. For thermal acceptability, its percentage was calculated to represent the rate of thermal acceptance. To avoid the impact of outliers, data sets with fewer than three entries per group were filtered out.

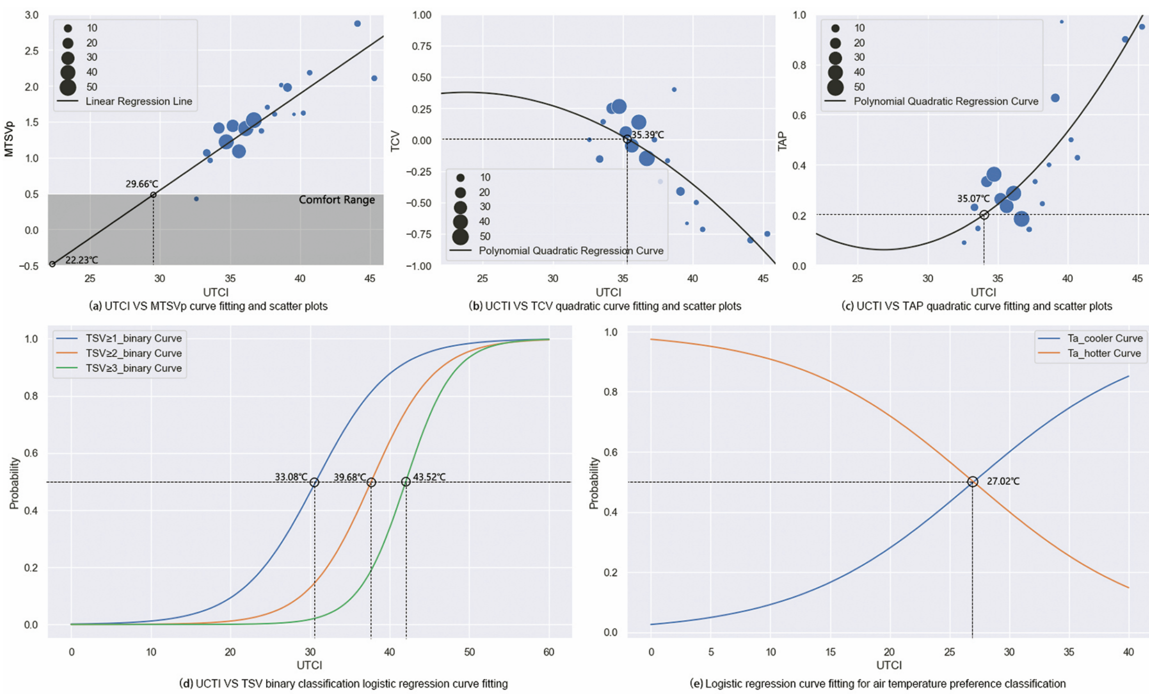
4.4.1 Neutral UTCI and neutral UTCI range

The quadratic linear fitting model in this study, specifically the R^2 value, did not show substantial enhancement compared to simple linear fitting, hence the choice of simple linear fitting to prevent overfitting. Figure 8(a) illustrates a simple linear fit between MTSVp and UTCI, establishing their relationship as MTSVp = 0.1346UTCI – 3.4916 (R^2 = 0.77). With a slope of 0.1346 in the linear fitting equation, it indicates that Suzhou's elderly have a thermal sensitivity to UTCI of 7.43°C/MTSVp, implying that a one-grade thermal sensation change occurs with a 7.43-degree rise in UTCI. The neutral temperature and its range are established using MTSVp = 0 and a ±0.5 range, resulting in a neutral temperature of 25.94°C and a range from 22.23°C to 29.66°C, where the range width corresponds to thermal sensitivity.

4.4.2 Thermal comfort UTCI threshold value

A quadratic linear fit was performed between thermal comfort vote TCV and UTCI, resulting in the following outcomes shown in Figure 8(b): TCV = –0.0028UTCI^2 + 0.1332UTCI – 1.2072 (R^2 = 0.62). Given that achieving comfort in the hot summer is nearly impossible and that changes in thermal comfort are continuous with qualitative changes occurring after a certain accumulation, inserting TCV = 0 into the equation yields a critical point of thermal comfort and discomfort at 35.39°C. Hence, it is observed that changes in thermal comfort perception are not immediately significant as UTCI rise from neutral, but the likelihood of thermal discomfort increases when the temperature reaches the critical point of 35.39°C.

FIGURE 8. Thermal benchmark fitting results.



4.4.3 Thermal acceptable range

The Unacceptable Rate of Perception (URP) refers to the percentage of votes for thermal unacceptability out of the total votes. Figure 8(c) presents a quadratic linear fit between the thermal unacceptability rate of the elderly and UTCI values, yielding the equation URP = $0.00274UTCI^2 - 0.14709UTCI + 2.03823$ ($R^2 = 0.69$). As per ASHRAE standards, the thermal acceptability range is defined where at least 80% of respondents deem it acceptable, implying the URP should be 20% or lower. By applying the standard of URP ≤ 20% to the calculations, the UTCI thermal acceptability range for the elderly in Suzhou during summer is determined to be between 19.41°C and 35.07°C. The upper limit of this range, 35.07°C, is very close to the critical value of thermal comfort, 35.39°C, thereby reinforcing the credibility of this thermal acceptability range.

4.4.4 Thermal rating ranges

The original UTCI has ten thermal ratings, but this study focuses only on summer, covering four levels from neutral to hot, excluding extreme hot or cold stress levels. In categorizing thermal ratings, most studies follow ASHRAE standards, defining each thermal rating within a range of ±0.5 of the corresponding thermal sensation value. Inserting –0.5, 0.5, 1.5, 2.5 into the simple linear fitting equation between MTSVp and UTCI, the calculated boundaries for each level are 22.23°C, 29.66°C, 37.09°C, and 44.51°C, respectively. Observing the curve of URV against UTCI, it is noted that the slope on the right side of the curve (the derivative of the original equation, 0.00274UTCI – 0.14709) increases with rising UTCI. Given that the original TSV is an ordinal categorical variable, it was converted into binary categories (TSVp ≥ 1, TSVp ≥ 2, TSVp ≥ 3), and binary logistic regression fitting was applied to each. Binary logistic regression results in Figure 8(d) are as follows: TSVp ≥ 1 Probability = 1/[1 + e^(0.2121UTCI – 6.5153)]; TSVp ≥ 2 Probability = 1/[1 + e^(0.2493UTCI – 9.3929)]; and TSVp ≥ 3 Probability = 1/[1 + e^(0.3340UTCI – 14.0346)]. Substituting Probability as 50% into the equation results in values of 0.5, 1.5, and 2.5, which correspond to 33.08°C, 39.68°C, and 43.52°C respectively.

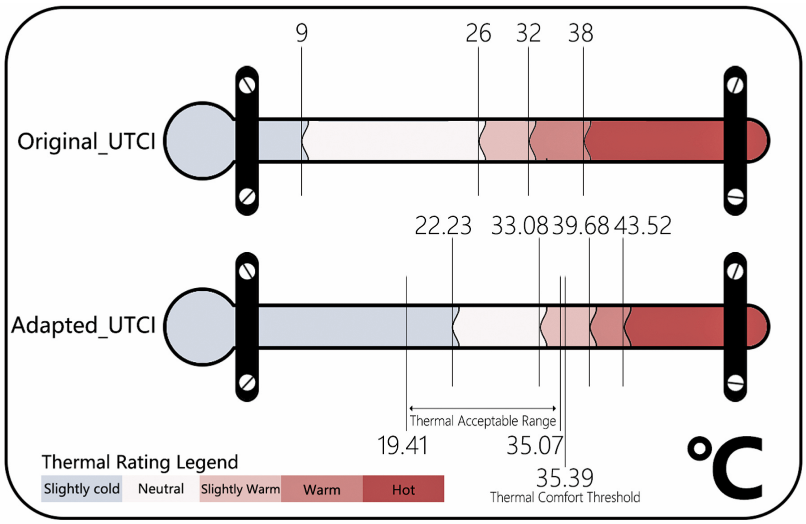
4.4.5 Preferred UTCI

Preferred UTCI refers to a condition where people neither like it too low nor too high, representing an ideal thermal environment state. The original data categorizes air temperature (Ta) preferences into three values: –1 (wish to lower), 0 (remain the same), and 1 (wish to increase). To quantify preferences for outdoor thermal environments, the votes for "no change" were evenly allocated to "lower" and "higher," resulting in the creation of two binary categorical variables, Ta_cooler and Ta_hotter, based on Desired_Ta = –1 and Desired_Ta = 1. Curves for "desiring lower temperatures" and "desiring higher temperatures" were drawn using logistic curve models, with their intersection point defining the preferred temperature. The approach to calculate the preferred temperature, results in a preferred UTCI of 27.02°C, as shown in Figure 8(e). The preferred UTCI of 27.02°C exceeds the earlier calculated neutral UTCI of 25.94°C, possibly indicating the elderly in Suzhou's adaptation to hot weather, resulting in their reduced inclination for lower temperatures.

5. DISCUSSION

During summer field investigations in the retirement communities of Suzhou, which is in a hot summer and cold winter region of China, this research gathered information about the outdoor

FIGURE 9. Comparison of UTCI adapted range with original range.



activity environment of the elderly. Utilizing machine learning techniques, physiological data was incorporated into thermal comfort assessment, and through statistical analysis the preferences of the elderly for outdoor activity environments and the factors affecting their thermal comfort were revealed. Grounded in these discoveries, the study chose a suitable comfort index for conducting thermal baseline calculations, offering directions for the design of outdoor environments in elderly communities within this climate zone.

5.1 Thermal perception of different outdoor built environments by older adults

When analyzing the thermal environment perceptions of various elderly groups, even given that site characteristics significantly affect meteorological parameters, the elderly's perceptions exhibit ambiguity. Elderly in group A did not perceive excessive heat. In the pathway spaces of sites B and E, the elderly felt moderate thermal sensation rating. Elderly in group F had similar thermal comfort and meteorological parameter preferences to group B but experienced a higher thermal sensation rating. Elderly in group C and H preferred neutral or slightly warm environments, with a greater need for cooling and dehumidification. Group D elderly had similar thermal comfort perceptions as group C. Elderly in group G experienced more intense thermal sensations than those in group C.

In the discussion comparing different spaces, it's not difficult to identify some basic mechanisms affecting thermal comfort in outdoor environments. Thermal comfort is closely related to the body's thermal balance, involving a balance between heat produced by metabolism and heat lost through convection, radiation, conduction, and evaporation (Mady et al., 2014). When the air temperature Ta is significantly higher than body temperature, an increase in Ta enhances heat exchange and raises the body's internal heat (González-Alonso et al., 1999), leading to an increase in the thermal sensation vote TSV. Likewise, enhanced solar radiation also raises the TSV (Abdallah et al., 2020). In areas with sparse tree cover, the higher TSV owing to greater solar radiation necessitates a more urgent demand for reduced sun exposure. Furthermore, the high moisture content of humid air improves its heat conduction properties over dry air (Jin et al., 2016). This is confirmed in behaviors of thermal adaptation, where some surveyed individuals perceive the cooling effect of tree shade to be less significant in southern regions than in northern ones, favoring movement to the shade of buildings instead. Air velocity (Va) affects evaporation efficiency. As Va increases, evaporation efficiency improves, aiding in heat dissipation (Saunders et al., 2005). This effect is most noticeable in high wind conditions, but in calm or low wind situations, it is not significant, resulting in no clear correlation between TSV and Va. The majority are content with the prevailing air velocity.

Microclimatic changes are influenced not only by meteorological factors but also play a significant role in meso- and micro-scale architectural environments (Allegrini et al., 2015). A higher degree of enclosure in building interfaces can create larger shaded areas, leading to a cooling effect (Middel et al., 2014). The two retirement communities in this study had different building heights, with higher air temperatures and thermal perceptions generally observed in the high-density community compared to the low-density one. Waterfront spaces usually have higher relative humidity (Cheung et al., 2021). In sites A and C, with similar temperatures and sparse vegetation, site C had stronger solar radiation, but A had higher humidity, leading to greater thermal discomfort in A. Variations in paving materials result in humidity differences (Wu et al., 2018). For instance, the tiling at site C retains more moisture than the plastic-asphalt mixture at site H. Vegetation can significantly reduce air temperature and solar radiation (Dimoudi & Nikolopoulou, 2003). In densely vegetated sites B and D, despite more activity, there was no significant increase in TSV.

With advancing age, elderly individuals exhibit reduced muscle mass and increased fat tissue, resulting in decreased skin sensory capacity, which may cause a blurred perception of temperature variations (Kenny et al., 2010). The research discovered that although sites D and F have distinct differences of site features and meteorological parameters, the perception of heat levels among these two groups of elderly was not significantly different. Additionally, a decline in blood circulation efficiency may cause the elderly to feel more intense sensations in extreme temperatures (Blatteis, 2011). In sites D, F, G, and H, when the air temperature exceeded 32°C, there was a significantly higher proportion of votes for the 'hot' thermal sensation rating. Consequently, elderly individuals of varying ages and health statuses exhibit differences in their choices of outdoor activity locations. Despite noticeable differences in temperature, humidity, and solar radiation at different sites, the elderly's subjective perception might be vague, resulting in less distinct awareness of differences in the thermal environment, potentially heightening the risk of heat stress injuries.

5.2 Ancillary role of physiological characteristics

By analyzing physiological parameters highly correlated with TSV (thermal sensation votes), the impact of thermal environments on the physiological state of the elderly can be analyzed objectively (Li et al., 2023), confirming the existence of differences in thermal perception among different spatial types. The variation in SpO2 mirrors the differing levels of oxygenation in various elderly groups, and the PI data exposes their circulatory states. The elderly in A, C, E, and F groups exhibit universally lower SpO2 compared to others, suggesting reduced oxygenation. The average SpO2 in group G is the highest, showing a better oxygenation status. The PI of groups B and D significantly differs from the rest, illustrating a notable impact of the thermal environment on blood circulation. Under hot conditions, the human body regulates its temperature by enhancing sweat production to release heat, which can result in fluid loss, altering the density and thickness of blood, consequently affecting blood oxygen saturation (Baker, 2019). For instance, when the temperature at site D is significantly lower than at F, the

SpO2 of the elderly in group D is notably higher than in group F. Moreover, to dissipate excess heat, the body dilates skin blood vessels, increasing skin blood flow, which leads to a higher Perfusion Index (Salloum et al., 2007). In environments with higher temperatures like in the D, F, G, and H groups, the PI values in the elderly are generally higher.

Compared to younger individuals, the elderly have a more ambiguous thermal perception, which may lead to less accurate judgments in their TSV (Soebarto et al., 2019). Consequently, this study incorporates objective physiological data to enhance the precision of thermal comfort assessments. After data cleansing (Chu et al., 2016) and handling outliers in box plots, it was observed that as the temperature increases, the thermal sensation tends to be hotter, and blood oxygen saturation usually decreases (Gallen & Macdonald, 1990), indicating a negative correlation between TSV and SpO2. Simultaneously, at elevated temperatures, the acceleration of blood flow results in a marked increase in the PI (Sessler et al., 2008), illustrating a positive correlation between TSV and PI. Pertaining to the connection between perceived temperature and pulse rate, given that PR is heavily affected by individual health conditions and might not distinctly represent thermal sensation, the correlation between TSV and PR is not pronounced in this study.

Considering the characteristics of the data, selecting an appropriate mathematical method is crucial for exploring the relationship between dependent and independent variables (Ferreira de Oliveira & Levkowitz, 2003). This study employed polynomial fitting, yielding results of R2 = 0.579, MSE = 0.398, MAE = 0.531, indicating the degree of association between physiological characteristics and TSV. The research further utilized LGBM regression, a gradient boosting tree algorithm effective for categorical variables (Du & Gou, 2023), significantly improving model efficacy with the ordered categorical variable TSV, as indicated by R2 = 0.695, MSE = 0.299, MAE = 0.416, proving more precise than polynomial fitting. The approach effectively adjusted for prior outliers and, by consolidating objective physiological data to produce TSVp, successfully tackled the subjectiveness of TSV, notably in enhancing the elderly's unclear judgment of thermal sensation.

5.3 Literature comparison of thermal benchmarks

Table 6 compares the thermal benchmarks of cities in different climatic zones, based on neutral UTCI, neutral UTCI range, thermal-sensitive UTCI, and thermally acceptable ranges. To control for seasonal variations, studies related to summer were selected for analysis. These studies encompass different locations such as pedestrian streets, campuses, parks, residential areas, and mixed zones. The subjects of the study include not only a mixed-age population but also specifically target the elderly, middle-aged, youth, children, and university students.

Neutral UTCIs are able to reflect the overall thermal sensory benchmarks for specific regions and populations. Comparison results shows that the summer neutral UTCI in hot summer and cold winter regions is usually higher than in cold and severe cold regions. However, Beijing is an exception due to its large urban scale, population density, and strong urban heat island effect, resulting in its neutral UTCI being significantly higher than other cold regions. Regarding age, the study in Shanghai shows that the neutral UTCI of the young is lower than that of the elderly, and lower than the elderly in Suzhou in this study. Compared to the mixed population in Chengdu and Wuhan, the neutral UTCI of the elderly in this study is higher, suggesting that the neutral UTCI of the elderly is generally higher. The neutral UTCI of the elderly in cold regions is slightly lower, possibly due to their lower adaptability to high temperatures compared to those in hot summer and cold winter regions. In Xi'an, the neutral

TABLE 6. Results of adapted UTCI in different outdoor thermal comfort studies.

City	Climate	Season	Context	Population	NUTCI (°C)	NUTCIR (°C)	TSUTCI (°C/TSV)	TAR (°C)	Analysis methods
Suzhou (This study)	HSCW	Summer	Retirement community	Elderly	25.9	22.2–29.6	7.4	19.4–35.1	bin 0.5°C, LR, 80% acceptability
Shanghai (Xue et al., 2020)	HSCW	Summer	Campus	Young/ Elderly	19.6/25.9	15.8–23.5/22.6–29.3	7.7/6.7		bin 1°C, LR
Chengdu (Wei et al., 2022)	HSCW	Summer	Urban park	Mixed ages	24.7	13.3–27.2	13.9	8.1–28.3	bin 1°C,LR, 80% acceptability
Wuhan (Huang et al., 2016)	HSCW	All year	Residential area	Mixed ages	19.2	11.1–27.4	16.3	15.2–28.8	bin 1°C, LR, 90% acceptability
Hongkong (Cheung and Jim, 2018)	HSWW	Summer	Urban park	Mixed ages	22.7	19.9–33.1		22.7–38.8	Logit, 80% acceptability
Beijing (Li et al., 2022)	C	Summer	Mixed area	Middle-aged/ Elderly	28.0/27.7	24.6–31.4/24.4–30.1	6.8/6.7	23.3–33.7/26.5–33.2	bin 1°C, LR, 80% acceptability
Xi'an (Huang et al., 2021)	C	Summer	Urban park	Children	17.8	11.4–24.2	12.8	3.7–21.2	bin 1°C, LR, 80% acceptability
Xi'an (Niu et al., 2020)	C	Summer	Campus	University students	24.9	20.7–29.2	8.5		bin 1°C, LR
Xi'an (Ma et al., 2021)	C	Summer	Urban park	Elderly people	17.5	4.9–22.1	17.2	6.8–30.0	bin 1°C, LR
Harbin (Zhu et al., 2020)	SC	Summer	Pedestrian street	Mixed ages	19.3	15.6–23.0	7.4	16.8–29.3	bin 1°C, LR, 80% acceptability
Harbin (Jin et al., 2019)	SC	Summer	Pedestrian street	Mixed ages	21.8	17.9–25.6	7.7	15.4–26.5	bin 1°C, LR, 90% acceptability

NUTCI = neutral UTCI; NUTCIR = neutral UTCI range; TSUTCI = thermal sensitive UTCI; TAR = thermal acceptable range; HSCW = hot summer and cold winter region; HSWW = hot summer and warm winter region; C = cold region; SC = serve cold region; LR = linear regression

UTCI of urban parks is lower than that of campuses due to a higher greening rate. The study of pedestrian streets in Harbin also shows variations in neutral UTCI, showing the significance of microclimate changes caused by the built environment. In terms of the neutral UTCI range, the upper and lower limits for the elderly in Suzhou are relatively high, second only to Hong Kong and Beijing, and close to the range for the elderly in Shanghai. In this study, the upper and lower limits of the neutral UTCI range for the elderly in Suzhou are 2.2°C and 0.5°C lower respectively than those for the elderly in Beijing, and higher by 17.3°C and 7.5°C respectively than those for the elderly in Xi'an. Although the overall neutral UTCI range for the elderly in Suzhou is lower than in Beijing, the thermal acceptable range is greater. In hot summer cold winter regions, the neutral UTCI range for the elderly is generally higher than other regions, possibly because they are more accustomed to outdoor interactive behavior. Cultural and social behavior can have an impact on thermal comfort that cannot be explained by traditional thermal comfort assessment methods alone (Elnabawi et al., 2016; Shooshtarian, 2019).

As a sensitive group, elderly people often feel heat earlier than other populations when temperatures rise, showing a higher thermal sensitivity and lower thermal sensitive UTCI. In regions with hot summers and cold winters, the elderly's thermal sensitive UTCI tends to be lower than that of other demographics. This study found that the thermal-sensitive UTCI for the elderly in Suzhou is 6.5°C UTCI/TSV and 8.9°C UTCI/TSV lower than the mixed populations in Chengdu parks and Wuhan residential areas, respectively. In Beijing, the elderly's thermal sensitive UTCI is 1°C UTCI/TSV lower than that of young people, a similar finding to studies in the Qinghai-Tibet Plateau (Yao et al., 2022) and Guangzhou (Fang & Hu, 2019). The increased thermal sensitivity in the elderly may be related to a decline in regulatory response capability and hemodynamic stability. The elderly's reduced ability to perceive heat changes results in a heightened sensitivity to temperature fluctuations (Blatteis, 2011). However, in Xi'an the thermal sensitivity of the elderly is lower than that of university students and children, possibly because the summer temperatures in cold regions are not very high, the warming range is small, and residents have lower expectations for temperature reduction.

Analysis shows that thermal benchmarks in the same climate zone are determined by the environmental features and demographic characteristics of the study region. Compared to other studies, the neutral UTCI and neutral UTCIR for the elderly in Suzhou are relatively high, indicating a higher thermal sensitivity. The elderly, owing to their long-term heat experience and adaptability, can better adapt to the rise in summer temperatures. However, their high sensitivity to warming also increases their risk of suffering from heat stress injuries.

6. CONCLUSION

In this study, 360 respondent elders (≧60 years old) were interviewed, all of whom were recreationally active in the outdoor open space of two retirement communities in Suzhou, China. Physiological data collection was added to the traditional thermal comfort survey and meteorological parameters. Based on this, the TSVp values were predicted by combining objective data with subjective evaluations through a machine learning model and revising the thermal benchmarks suitable for Suzhou senior living communities. The main findings are as follows.

1. The microclimate of different outdoor sites varies due to combinations of enclosure forms, paving materials, and vegetation density. Increased enclosure height leads to a general decrease in air temperature, the material of paving impacts relative humidity to some extent, and vegetation density affects changes in solar radiation. Although there are objective differences in the thermal environment, the subjective thermal perception of the elderly is ambiguous, leading to less noticeable perception of these differences and increasing the risk of heat stress injuries.
2. The thermal sensation voting considered the combination of subjective voting with objective physiological parameter assistance, more accurately predicting thermal

sensation voting for the elderly. Polynomial and LGBM regression models reached fitting accuracies of 0.579 and 0.695, mean squared errors (MSE) of 0.398 and 0.299, and mean absolute errors (MAE) of 0.531 and 0.416. After evaluating the model's performance and its predictive results, the LGBM regression model was chosen. This model was used to make more accurate TSVp predictions based on SpO2 and PI.

3. Data was binned at 0.5° intervals, and linear and logistic regression were used to establish thermal benchmarks. The neutral UTCI and its range were determined to be 25.94°C and 22.23°C–29.66°C, respectively. The threshold for thermal comfort was set at 35.39°C. For 80% of elderly residents in the retirement community, the thermal acceptable range was found to be 19.41°C–35.07°C. The adapted thermal ratings were defined as neutral 22.23°C–33.08°C, slightly warm 33.08°C–39.68°C, warm 39.68°C–43.52°C, and hot above 43.52°C. The preferred UTCI was identified as 27.02°C.
4. Based on literature comparisons, there are significant differences in the summer neutral UTCI and neutral UITCIR among different populations in various study areas. For the elderly in regions with hot summers and cold winters, both these measures are higher compared to other local populations, and also surpass those in most cold and extremely cold areas. The thermal-sensitive UTCI for the elderly in regions with hot summers and cold winters is lower than that of other demographics, indicating a higher thermal sensitivity among the elderly who are more quickly affected by higher thermal stress during warming, increasing the risk of heat stress injuries.

Limitations and future research. The limitations of this study are that it focused solely on outdoor thermal comfort during summer, had a limited sample size, and did not analyze the impact of personal parameters like age and gender, as well as operational parameters like clothing thermal resistance and activity thermal resistance, on thermal comfort. Future research plans include expanding the study to transitional seasons and winter, adding more retirement community cases and sample sizes, while also integrating auditory and visual factors, utilizing climate software simulations, and proposing detailed strategies to improve the thermal comfort of outdoor activities in retirement communities based on actual spatial behavior and health conditions.

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