

Article

The Impact of Elements from Classical Chinese Gardens on Thermal Comfort Within Architectural Gray Spaces—The Case of Xishu Celebrity Memorial Garden

Yuting Fu , Dingying Ye *, Yiyang He, Xi Li and Xinxin Huang

College of Landscape Architecture, Sichuan Agricultural University, No. 211, Huimin Road, Wenjiang District, Chengdu 611130, China; 2023210005@stu.sicau.edu.cn (Y.F.); yiyanghe755@gmail.com (Y.H.); lixi@sicau.edu.cn (X.L.); xinxinh269@gmail.com (X.H.)

* Correspondence: 41247@sicau.edu.cn

Abstract

Against frequent extreme heat, landscaped green spaces cool, humidify, and mitigate urban heat islands, also boosting thermal comfort. Classical Chinese garden “gray spaces” are transitional gathering zones with strong microclimate-regulating potential, yet systematic research on their mechanisms in Western Sichuan memorial gardens remains limited. This study first reveals their thermal characteristics; establishes a refined classification system; uncovers nonlinear links between garden elements, spatial form, and thermal comfort; and proposes optimization strategies. Key findings: (1) Gray spaces show notable microclimate regulation. Internal air temperatures drop by 0.8–4.3 °C, relative humidity rises by 2.2–22.33%, and average PET decreases by 3.1 °C, effectively relieving thermal stress. (2) Thermal comfort is closely related to gray space types, with open halls performing best due to their strong sense of enclosure and shading. (3) Plant-dominated and hybrid spaces are superior to water-dominated ones. PET is negatively correlated with 40–70% plant canopy and 20–30% water coverage, while excess water leads to stuffiness. Hybrid spaces reach ideal blue–green synergy at 50–60% canopy and 20–30% water. (4) The summer PET comfort threshold for Western Sichuan gray spaces is 29.1–31.5 °C (neutral at 30.2 °C), higher than European standards, reflecting local adaptation to a hot–humid climate and guiding microclimate-adaptive design.

Keywords: celebrity memorial gardens of Xishu; architectural gray space; human thermal comfort; garden elements



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1. Introduction

In recent years, the trend of global warming has greatly exceeded the natural variability of the climate system observed over the past thousands of years. Multiple lines of evidence show that human activities have increased global average temperatures by about 1.1 °C above pre-industrial levels, with the frequency and severity of extreme heat events continuing to rise [1]. China, with its vast territory, complex topography, and diverse climate types, has experienced frequent compound extreme heat and humidity events alongside rapid economic growth and urbanization, significantly impacting residents’ lives [2]. By the summer of 2025, many regions of the Northern Hemisphere, including China, are expected to continue experiencing higher temperatures [3]. Meanwhile, urbanization has accelerated greenhouse gas emissions, intensifying the urban heat island effect. This causes local temperatures to rise well above those of surrounding suburban areas, worsens air quality,

and directly threatens residents' health and well-being. The frequent occurrence of such extreme weather not only undermines the United Nations Sustainable Development Goal (SDG 3) of "Good Health and Well-being" by increasing heat-related health risks but also significantly changes how residents interact with urban green spaces, leading to new usage patterns and demands. Faced with rising climate challenges, beyond large-scale adaptation strategies at the global and regional levels, actively designing and improving microclimates at the local level—where people directly connect with their environment—has become a crucial way to enhance the resilience and the feeling of thermal comfort for people in the housing estates where they live.

Currently, the academic community is increasingly focused on mitigating urban heat islands and promoting low-carbon environments. Extensive research indicates that green spaces play an indispensable role in ecological regulation and in protecting human health from the physiological impacts of high temperatures. Most related studies have primarily focused on the cooling effects of green areas [4–9], blue–green spaces promoting human health and well-being [10–12], the impact on human mental health [13–15], reducing environmental pollution in surrounding areas [16,17], and other positive effects. Therefore, through effective urban green space planning and architectural design strategies, appropriately designed landscape elements can significantly reduce heat stress [18,19], enhance local climate comfort [20,21], promote sustainable urban development [22], and improve the well-being of surrounding residents [23–25].

In 1947, Landsburg first introduced the concept of climate within the surface boundary layer, influenced by vegetation, soil, and topography [26]. Current research primarily focuses on the mechanisms by which landscape elements regulate the microclimate [27–29], human thermal comfort [30,31], and digital simulation variables [32–34]. Methodologies have evolved from physical measurements to integrated evaluations that incorporate subjective perceptions and behavioral patterns. Globally, studies on the climate adaptability of historic buildings and landscapes have emerged as a cross-disciplinary hotspot at the intersection of architecture, heritage conservation, and sustainable design [35–37]. Among these, architectural "gray spaces" have emerged as a significant area of research in microclimate and human comfort, given their unique spatial attributes and high climate sensitivity. Historical garden structures' gray spaces exhibit frequent visitor activity and distinctive climate adaptability. However, research on thermal comfort in classical garden gray spaces remains limited, primarily focusing on passive design strategies in Mediterranean colonnades [38,39], Islamic courtyards and arcades [40,41], and Japanese gray spaces (Engawa) [42]. Research on classical Chinese gardens remains relatively scarce, with most studies concentrated on gardens in the Jiangnan and Lingnan regions. These studies tend to emphasize visual aesthetics and human sensory perception. Given the specific climatic conditions of Western Sichuan—characterized by year-round low-hanging clouds, limited sunlight, and high humidity [43]—systematic investigations into the mechanisms regulating the microclimate in gray spaces are particularly lacking. Notably absent are in-depth quantitative analyses that reveal the relationships between spatial form, interface materials, vegetation coupling, and other factors, and thermal environment parameters and users' subjective comfort perceptions.

In response to the current research landscape and practical circumstances, this study pioneers a focus on classical memorial gardens dedicated to historical figures. It establishes a comprehensive evaluation system for thermal comfort in architectural gray spaces within Xishu Memorial Gardens, determining human thermal comfort thresholds and clarifying thermal environment variations across gray space types and element configurations. This provides a reusable methodological foundation for subsequent research. Second, through quantitative analysis of garden elements, architectural gray space morphology, and thermal

comfort, this study elucidates the coupling mechanism among these three factors. It validates the integration pathway between traditional garden ecological wisdom and modern thermal comfort theory, empirically demonstrating that the spatial strategies of Xishu memorial gardens—such as shading, ventilation, and humidity regulation—have contemporary climate-adaptation value. This provides theoretical and practical support for translating traditional garden wisdom into urban green space design and heritage conservation. Finally, it summarizes the combinatorial characteristics of spatial types and elements, along with their thermal environmental effects; analyzes and optimizes thermal comfort threshold ranges; and proposes spatial creation strategies and design pathways based on thermal comfort optimization.

2. Materials and Methods

This study employs a combined objective–subjective research methodology, integrating field measurements and questionnaire surveys to investigate the relationship between human thermal comfort and landscape elements in commemorative gardens dedicated to historical figures of Xishu. The research primarily involves the following five steps: (1) selecting study areas, measuring their microclimate data, and quantifying landscape elements at measurement points; (2) distributing thermal comfort questionnaires within the selected areas to gather visitors’ subjective thermal perceptions and comfort ratings; (3) coupling subjective and objective data to calibrate human thermal sensation and establish thermal comfort thresholds; (4) analyzing the relationships and mechanisms between garden elements and architectural gray spaces; and (5) proposing optimization strategies to enhance thermal comfort in garden architectural gray spaces (Figure 1).

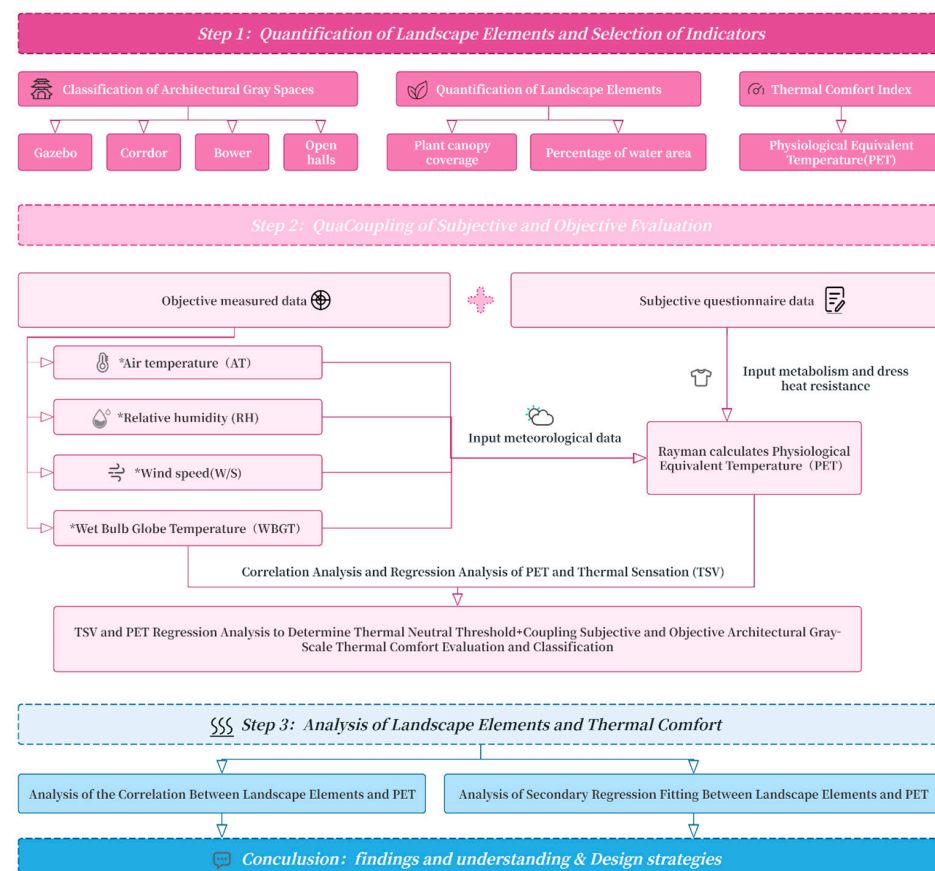


Figure 1. Technical roadmap.

2.1. Research Area Classification and Actual Survey Points

In classical Chinese gardens, architectural forms include pavilions, terraces, towers, corridors, halls, chambers, and gazebos, among others [44,45]. Gray spaces commonly appear as platforms, eaves, corridors, pavilions, and waterside pavilions [46]. Based on this classification and incorporating the concept of gray space, the memorial gardens of renowned figures in Xishu are categorized into four types: pavilion–platform, corridor–bridge, pavilion–veranda, and open hall.

The gardens of Xishu, centered on the Chengdu Plain, constituted a regional garden system primarily composed of memorial gardens dedicated to famous figures and temple gardens, supplemented by imperial tombs, private residences, and public gardens [47]. Based on their distribution patterns, this study examines the impact of gray spaces on thermal comfort in memorial gardens dedicated to prominent figures in Chengdu.

Landscape microclimate refers to the localized climatic conditions resulting from the combined effects of four core elements: topography, vegetation, water bodies, and architecture. Due to the scarcity of stone materials in the Western Shu region, gardens predominantly feature water landscapes as their primary attraction, with mountain scenery serving as a secondary element. Existing gardens rarely present rock formations as the main focal point for appreciation; instead, hills are typically earthen mounds of limited height [46]. Moreover, prior studies have shown that rock formation orientation has a negligible effect on the microclimate [48]. To effectively control for variables, this research employs architectural gray space as the primary framework, focusing specifically on two components: vegetation and water features. Following a quantitative analysis of the elements present in commemorative gardens dedicated to notable figures in Chengdu, and a comprehensive assessment of the coverage of various types of architectural gray spaces along with the proportional representation of garden elements, four gardens were ultimately selected for field investigation: East Lake, Gui Lake, YanHua Lake, and Temple of Marquis (Table 1 and Figure 2).

Table 1. Proportion of landscape elements in Xishu celebrity memorial gardens.

Gardens	Area (m ²)	Water Area	Building Area	Road and Paved Area	Green Area
East Lake	18,100	4700 (26%)	2900 (16%)	2500 (12.8%)	8000 (45.2%)
Gui Lake	45,300	15,000 (33.2%)	6500 (14.3%)	7900 (17.4%)	15,900 (35.1%)
Temple of Marquis	50,100	6000 (12%)	8200 (16.4%)	19,800 (39.5%)	16,100 (32.1%)
Yanhua Lake	33,900	8700 (25.7%)	6000 (17.7%)	7100 (20.9%)	12,100 (35.7%)

2.2. Quantification of Landscape Elements and Classification of Measurement Points

Aquatic features and vegetation are essential parts of the landscape that greatly improve spatial comfort and microclimatic conditions [49,50]. This study specifically examines these two elements. First, floor plans were created in AutoCAD 2021 and then imported into ArcGIS 10.2 to outline Areas of Interest (AOIs) with a 10 m radius around each building, defining the analysis parameters. Contour data were then exported back to AutoCAD to measure the surface area of water bodies and the extent of tree canopy coverage within each AOI. These measurements were used to determine average proportions, which guided the segmentation of landscape elements, as shown in Figure 3.

We examined landscape elements within a 10 m radius of the gray spaces in four garden structures. The average plant canopy cover was 44.38%, with each bar representing canopy coverage at each measurement point across the four gardens. The average proportion of water body area was 23.42%, and each bar in the figure shows the proportions

of water body areas at each measurement point across the four gardens (Figure 4). Using these averages as quantitative criteria, the landscape elements were further categorized.

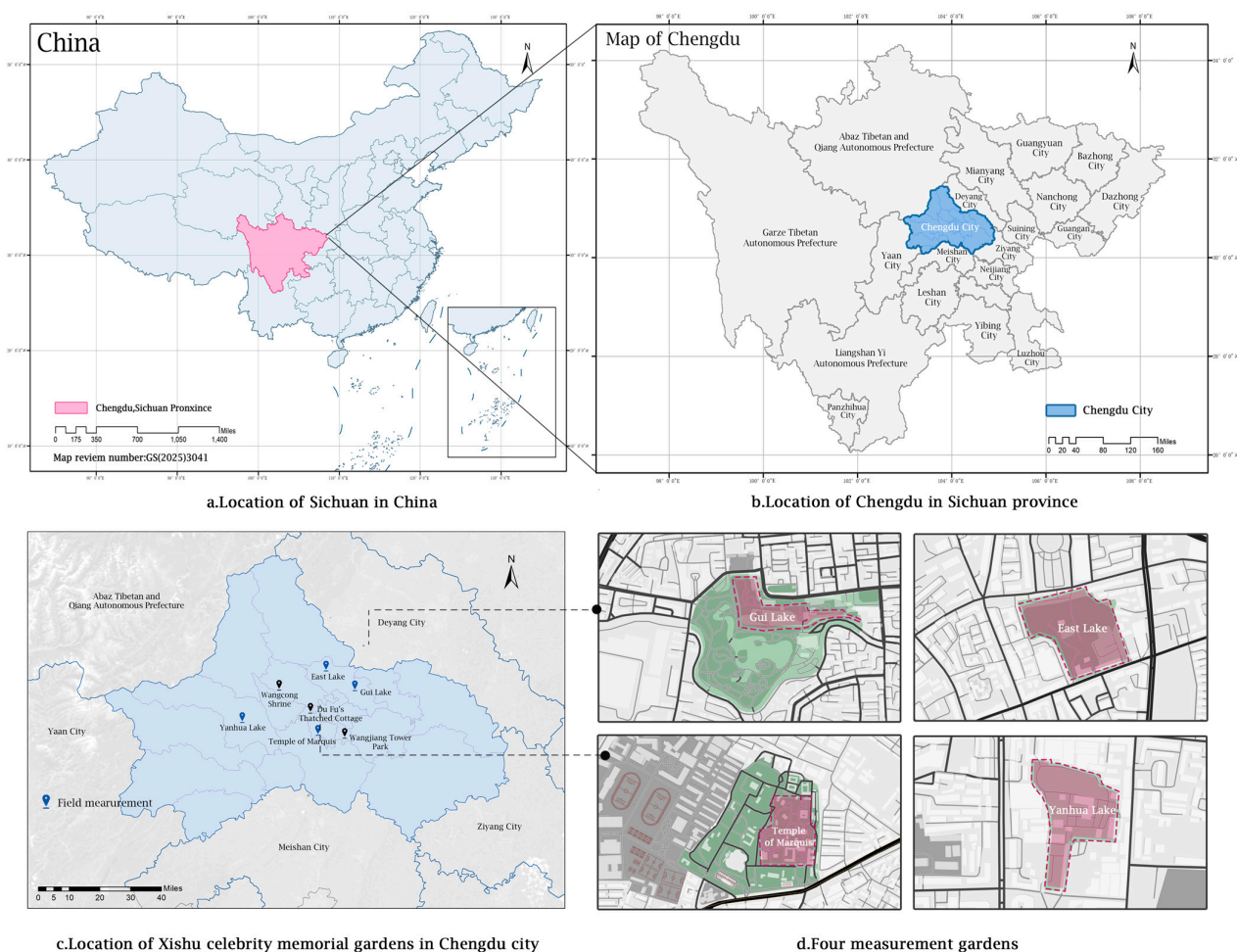


Figure 2. Location analysis. (a) Location of Sichuan in China. (b) Location of Chengdu in Sichuan province. (c) Location of Xishu celebrity memorial gardens in Chengdu city. (d) Four measurement gardens (image source: drawn by author).

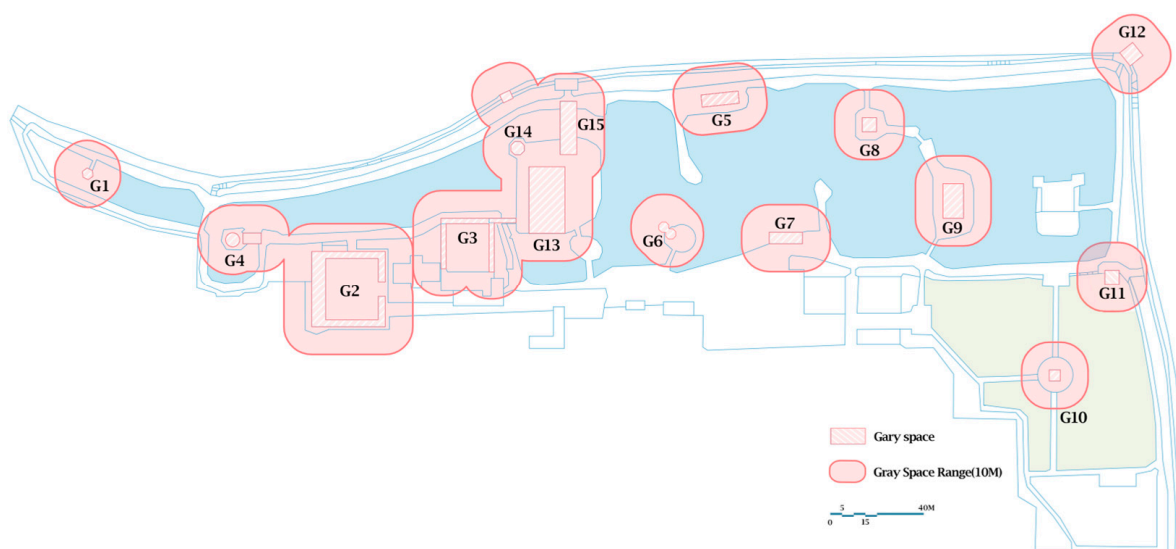


Figure 3. Illustration of measurement points and their radius ranges for garden building gray spaces (Gui Lake).

In summary, the architectural gray space measurement points were categorized into three distinct groups: plant-dominant, defined by tree coverage exceeding the average without water bodies, or average tree coverage with water bodies below the average; water-dominant, characterized by water body proportions surpassing the average but with plant canopy coverage below the average; and hybrid, which showed a combination of above-average and below-average values for these variables and was relatively common across the four gardens studied.

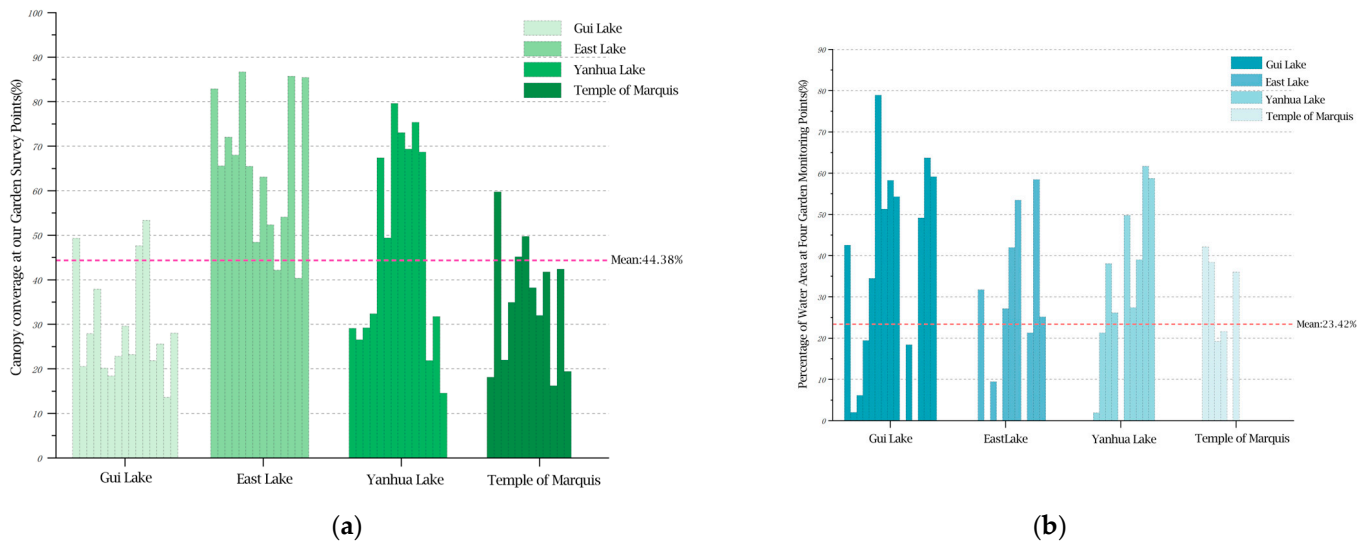


Figure 4. Percentage distribution of landscape elements at each point: (a) canopy coverage at each measurement point; (b) percentage of water area at each measurement point.

Of the 55 measurement points, gazebo was the largest group ($n = 23$), followed by bower ($n = 15$) and corridor ($n = 12$), whereas open halls were the least frequent ($n = 5$), predominantly located in the Temple of Marquis and Yanhua Lake. When categorized by garden elements, plant-dominant sites were the most numerous ($n = 25$), with hybrid-type ($n = 16$) and water-dominant ($n = 14$) sites occurring in comparable numbers. The distribution of each site type is detailed in Table 2.

Table 2. Classification of measurement points across the four gardens.

Gardens	Ponits	Plant Proportion (%)	Water Proportion (%)	Types of Gray Spaces	Types of Landscape Elements
East Lake	E1	82.88	0	Gazebo	Plant
	E2	65.61	0	Bower	Plant
	E3	72.02	0	Gazebo	Plant
	E4	68.03	31.76	Gazebo	Hybrid
	E5	86.68	0	Bower	Plant
	E6	65.49	9.45	Corridor	Plant
	E7	48.46	0	Gazebo	Plant
	E8	63.1	27.15	Corridor	Hybrid
	E9	52.35	41.96	Bower	Hybrid
	E10	39.19	53.47	Bower	Water
	E11	54.13	0	Bower	Plant
	E12	85.73	21.33	Gazebo	Plant
	E13	40.37	58.47	Bower	Water
	E14	85.45	25.21	Gazebo	Hybrid

Table 2. *Cont.*

Gardens	Ponits	Plant Proportion (%)	Water Proportion (%)	Types of Gray Spaces	Types of Landscape Elements
Gui Lake	G1	49.35	42.54	Gazebo	Hybrid
	G2	20.6	2	Corridor	Hybrid
	G3	27.92	6.14	Corridor	Hybrid
	G4	37.96	19.44	Bower	Hybrid
	G5	20.19	35.51	Bower	Water
	G6	18.45	78.95	Gazebo	Water
	G7	22.86	51.29	Bower	Water
	G8	29.6	58.29	Gazebo	Water
	G9	23.24	54.28	Bower	Water
	G10	47.67	0	Gazebo	Plant
	G11	53.36	18.4	Gazebo	Plant
	G12	21.9	0	Gazebo	Plant
	G13	25.58	49.15	Corridor	Water
	G14	13.6	63.72	Gazebo	Water
	G15	28.02	56.12	Bower	Water
Temple of Marquis	M1	18.17	0	Open halls	Plant
	M2	59.76	0	Open halls	Plant
	M3	21.99	42.16	Gazebo	Water
	M4	34.96	38.4	Corridor	Hybrid
	M5	45.16	19.22	Corridor	Plant
	M6	49.77	21.6	Gazebo	Hybrid
	M7	38.22	0	Gazebo	Plant
	M8	32.01	36.05	Bower	Water
	M9	41.81	0	Open halls	Plant
	M10	16.22	0	Open halls	Plant
	M11	42.4	0	Corridor	Plant
	M12	19.46	0	Corridor	Plant
YanHua Lake	Y1	29.12	0	Open halls	Plant
	Y2	26.59	0	Corridor	Plant
	Y3	29.24	0	Gazebo	Plant
	Y4	32.37	1.9	Gazebo	Plant
	Y5	67.42	21.3	Gazebo	Hybrid
	Y6	49.4	38.07	Gazebo	Hybrid
	Y7	79.6	26.17	Gazebo	Hybrid
	Y8	73.06	49.79	Corridor	Plant
	Y9	69.36	0	Bower	Hybrid
	Y10	75.37	27.41	Corridor	Hybrid
	Y11	68.68	39.02	Open halls	Hybrid
	Y12	21.9	61.86	Open halls	Water
	Y13	31.78	58.72	Gazebo	Water
	Y14	14.59	0	Gazebo	Plant

2.3. Field Measurements and Questionnaire

At present, the majority of research methodologies for thermal comfort rely on empirical data obtained through a combination of field surveys and in situ measurements to evaluate and analyze thermal comfort [49–51]. This study follows the framework illustrated in Figure 1, as previous research indicates that the moderating effect of landscape elements on the microclimate is most pronounced during the summer [52]. Given the sweltering, humid climate of Western Sichuan, data from the Chengdu Wenjiang National Meteorological Observatory indicate that, in most years over the past decade, the summer season has exceeded the long-term average. Since the 1970s, 1980s, and 1990s, Chengdu's summer season has shown a trend of increasing length each year, with a notably rapid acceleration observed between 2021 and 2024. According to China's 24 solar terms, the period from Major Heat to the Start of Autumn is the hottest time of the year. During this

period, the sun's direct rays are closest to the Tropic of Cancer, and heat accumulation on the ground reaches its peak. In 2025, Major Heat fell on 22 July, so we chose consecutive days with clear or partly cloudy weather and no rainfall in the preceding three days (28–30 July 2025) within this hottest window to conduct our measurements. Therefore, measurements were scheduled for three consecutive days, from 28 to 30 July 2025, between 9:00 a.m. and 5:00 p.m. at each observation point, with data averaged arithmetically. An unshaded, hard-surfaced control point was established outside the garden, and thermal comfort questionnaires were distributed simultaneously. Table 3 displays the daily weather data collected by the Chengdu Meteorological Station. Handheld instruments (Taiwan Hengxin AZ87786: Manufacturer: AZ Instrument Corp., Sourced from Beijing, China; Penglich PLC-16026: Manufacturer: Beijing Penglich Technology Co., Ltd., Sourced from Beijing, China) were used to record air temperature, relative humidity, wind speed, and black globe temperature at a height of 1.5 m. The measurement accuracy of the Taiwan Hengxin AZ8778 is ± 0.6 °C for air temperature, $\pm 5\%$ RH for relative humidity, and ± 1 °C for black globe temperature, while the measurement accuracy of the Penglich PLC-16026 is ± 0.3 m/s.

Table 3. Climate conditions of Chengdu on the Measurement Day.

Field Measurement Date	Maximum Air Temperature (°C)	Minimum Air Temperature (°C)	Weather Conditions	Wind Direction	Wind Speed
28 July 2025	37	25	Clear sky	Southwest wind	Wind force 2
29 July 2025	39	25	Clear sky	Northwest wind	Wind force 2
30 July 2025	38	26	Partly cloudy	West wind	Wind force 2

Among the prevalent thermal comfort indices are the PET, UTCI, SET*, and PMV. Research indicates that PMV and SET* provide accurate assessments of thermal comfort within relatively stable indoor environments, whereas PET and UTCI are better suited for evaluating dynamic outdoor conditions [48]. PET effectively quantifies thermal comfort by synthesizing multiple factors into a single temperature metric. Beyond meteorological parameters such as air temperature, humidity, wind speed, and mean radiant temperature, PET also incorporates individual-specific variables, including metabolic rate, activity-related heat production, and clothing insulation. Expressed in degrees Celsius (°C), PET closely matches human thermal perception, thereby offering advantages over alternative indices [53]. Consequently, this study employs PET as the primary indicator for assessing outdoor thermal comfort.

During data collection, one staff member conducted the measurements while another recorded the results. In addition to collecting the measurement data, two other staff members distributed questionnaires in real time, simultaneously with the measurements. The questionnaire survey consisted of three main sections: (1) Basic information about the participants (age, gender); (2) A survey of the participants' thermal comfort and sensations; (3) The respondent's activity level and clothing status during the past 20 min. According to the statistics, the average thermal resistance of the respondents' clothing was about 0.9 clo. Overall, 48% of the respondents were sitting still, while 43.9% were walking. Consequently, the average of these two activity levels was used as the standard for calculating human comfort, which corresponds to an activity level of approximately 90 W/m² (1.5 m/s).

The PET calculations in this study were primarily conducted using RayMan 3.1 software, including air temperature, relative humidity, wind speed, mean radiant temperature, human metabolic rate, and clothing thermal resistance. Because the mean radiant temperature could not be directly measured in this study, it was estimated using the black-body temperature.

3. Results

Based on the data collected from various monitoring points in the gray spaces of landscape architecture, outliers were initially removed using the 3σ criterion. Additionally, cross-validation was performed on synchronized data from multiple instruments to eliminate measurement errors caused by instrument-specific and environmental interference; meteorological data collected over three days were averaged. Since the instruments used in this test could not directly measure the mean radiant temperature (MRT) needed for PET calculations, the MRT formula specified in ISO 7726 was applied [54]. The measured air temperature, black globe temperature, and wind speed were substituted into the formula to calculate MRT point-by-point and hour-by-hour. A questionnaire survey was conducted concurrently with the meteorological data collection. Statistical analysis showed that the average clothing thermal resistance of the test subjects was approximately 0.9 clo. Among the subjects, 48% were seated, and 43.9% were walking; therefore, the average activity level of these two groups was used as the standard for calculating human comfort, corresponding to about 90 W/m^2 (1.5 MET). By combining the average activity level from the questionnaire with parameters such as clothing thermal resistance, the following variables were entered into RayMan software: air temperature, relative humidity, instantaneous wind speed, mean radiant temperature, clothing thermal resistance, and human metabolic rate. Additionally, data for men and women of standard height and weight were entered into RayMan for calculation. A comparison showed that gender had little effect on PET differences (within $0.1 \text{ }^\circ\text{C}$); therefore, a 35-year-old male with a height of 175 cm and a weight of 70 kg was used as the standard for calculating the physiologically equivalent temperatures at each measurement point. Finally, these temperatures were coupled and calibrated with questionnaire data to establish thermal comfort thresholds for the architectural void spaces within the Xishu memorial celebrity garden. These results were then analyzed in relation to the landscape elements surrounding the architectural voids.

3.1. Analysis of the Coupling Between Subjective and Objective Outcomes

3.1.1. Analysis of Field Measurements and Questionnaire Results

A preliminary analysis of objective meteorological data reveals differences between the architectural void spaces within the Xishu celebrity memorial garden and the environmental conditions at external reference points. Furthermore, the synergistic interaction of various landscape elements within the garden creates a cooling and humidifying effect on the architectural voids. During the testing period, air temperatures at various monitoring points decreased by $0.8\text{--}4.3 \text{ }^\circ\text{C}$, relative humidity increased by $2.2\text{--}22.33\%$, wind speeds showed no significant patterns, and the average PET value decreased by $3.1 \text{ }^\circ\text{C}$. The thermal environment and thermal comfort of the architectural void spaces within the garden were superior to those outside, indicating that the garden's landscape elements can significantly improve the microclimate and regulate human thermal comfort. Among the four types of architectural void spaces, the range of PET values for human thermal comfort was ranked as follows: Gazebos > Corridors > Bowers > Open halls. Among these, the most comfortable architectural gray space type is the open hall, which is the space closest to an indoor environment among the four categories. Its heavy roof and solid walls provide all-weather shade protection; however, the high enclosure of the open hall, while blocking radiation, may sacrifice open views and the flow of natural ventilation.

A statistical comparison of PET values across the four gardens (Figure 5) shows that those at Gui Lake mostly cluster between 35 and $37 \text{ }^\circ\text{C}$, while the other three gardens mainly range from 33 to $34 \text{ }^\circ\text{C}$. The extreme PET values are as follows: Gui Lake ($40.1 \text{ }^\circ\text{C}$) > Temple of Marquis ($39.2 \text{ }^\circ\text{C}$) > YanHua Lake ($39.0 \text{ }^\circ\text{C}$) > East Lake ($38.6 \text{ }^\circ\text{C}$). In terms of distribution, YanHua Lake shows a wider PET range, indicating greater spatial

variability in its thermal environment, whereas Gui Lake shows a more concentrated distribution, suggesting a relatively uniform thermal environment. Gui Lake features a natural design with extensive water bodies that connect throughout the park. The prominence of water bodies in regulating the microclimate, along with limited vegetation cover, may further homogenize the thermal environment. At the same time, the combined effects of water evaporation and radiation reflection contribute to higher PET extremes in this garden compared to the others. Thus, the ratio of vegetation coverage to water bodies and their spatial arrangement significantly impact thermal comfort in architectural gray spaces. Vegetation shading and evapotranspiration help lower PET, while water bodies might increase thermal discomfort during high temperatures and humidity.

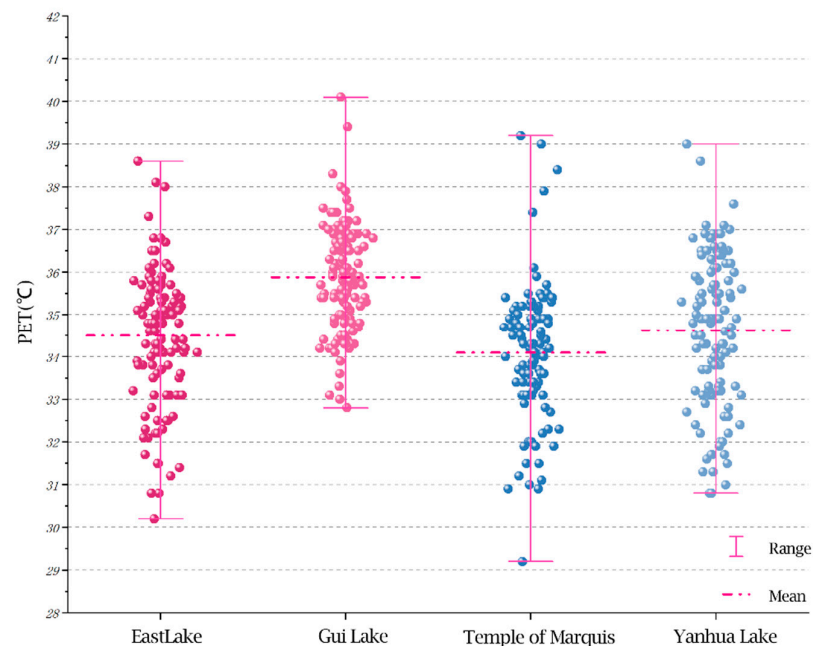


Figure 5. Overview of PET distribution across monitoring points in the four gardens.

In addition to objective measurements, this study simultaneously administered a subjective questionnaire survey targeting local tourists and nearby residents. A total of 819 valid responses were obtained from the four gardens under investigation. Statistical analyses indicated that none of the participants reported thermal sensations categorized as “very cold,” “cold,” or “cool.” Concerning thermal comfort, 60.57% of respondents indicated feeling either “very comfortable” or “comfortable,” a proportion substantially exceeding the 6% who described their thermal sensation as “moderate.” These results suggest that within the gray spaces of Xishu’s memorial garden architecture during the summer season, the spectrum of human thermal comfort is notably broad. Even when thermal sensations deviate from the “moderate” range toward slightly cooler or warmer conditions, visitors generally remain comfortable.

In addition to the overall analysis, this study’s questionnaire also examined age and gender, as shown in Tables 4 and 5. Regarding heat perception, the highest proportions of respondents reporting “hot” and “very hot” were among those aged 50 and older, followed by those aged 30–50 years old, and then those under 30. Sensitivity to heat decreases significantly with age; older adults have a higher threshold for perceiving thermal stimuli and are thus more tolerant of high temperatures [55,56]. From a gender perspective, the percentage of men reporting a sensation of heat (22.6%) was slightly higher than that of women (21.7%), indicating that men are somewhat more heat-tolerant than women. This may be because men generally have greater muscle mass, lower body fat percentage, and

a more favorable body surface area-to-body weight ratio, which results in greater heat production and more efficient heat dissipation [57,58]. In contrast, women tend to have lower sweat rates and less overall heat loss, leading to weaker heat tolerance compared to men.

Table 4. Statistical analysis of thermal sensation vote (TSV) by age and gender.

Thermal Sensation		Very Cold (−4)	Cold (−3)	Cool (−2)	Slightly Cool (−1)	Moderate (0)	Slightly Warm (+1)	Warm (+2)	Hot (+3)	Very Hot (+4)
Gender	Men				6 (1.5%)	23 (5.9%)	130 (33.3%)	143 (36.7%)	75 (19.2%)	13 (3.3%)
	Women				7 (1.4%)	26 (6.1%)	146 (34.0%)	157 (36.6%)	72 (16.8%)	21 (4.9%)
Age	<30 years old				5 (2.2%)	15 (6.6%)	70 (30.8%)	80 (35.2%)	45 (19.8%)	12 (5.3%)
	30–50 years old				5 (1.5%)	20 (6.1%)	112 (34.0%)	120 (36.5%)	55 (16.7%)	17 (5.2%)
	>50 years old				3 (1.6%)	14 (5.3%)	94 (35.7%)	100 (38%)	47 (17.9%)	5 (1.9%)
Total	819				13 (1.6%)	49 (6.0%)	276 (33.7%)	300 (36.6%)	147 (17.9%)	34 (4.2%)

Table 5. Statistical analysis of thermal comfort vote (TCV) by age and gender.

Thermal Comfort		Extremely Comfortable (+2)	Relatively Comfortable (+1)	Less Comfortable (−1)	Extremely Uncomfortable (−2)
Gender	Men	66 (16.9%)	170 (43.6%)	98 (25.1%)	56 (14.4%)
	Women	74 (17.2%)	186 (43.4%)	110 (25.6%)	59 (13.8%)
Age	<30 years old	30 (13.2%)	90 (39.6%)	65 (28.6%)	42 (18.5%)
	30–50 years old	55 (16.7%)	145 (44.1%)	85 (25.8%)	44 (13.4%)
	>50 years old	55 (20.9%)	121 (46.0%)	58 (22.1%)	29 (11.0%)
Total		140 (17.1%)	356 (43.5%)	208 (25.4%)	115 (14.0%)

Following the compilation of voting results on thermal sensation and thermal comfort across the four gardens, the study used percentage stacked bar charts to display the data, thereby accommodating differences in sample sizes among the gardens (Figure 6). Generally, consistent trends were observed across the gardens in the assessments of both thermal sensation and thermal comfort.

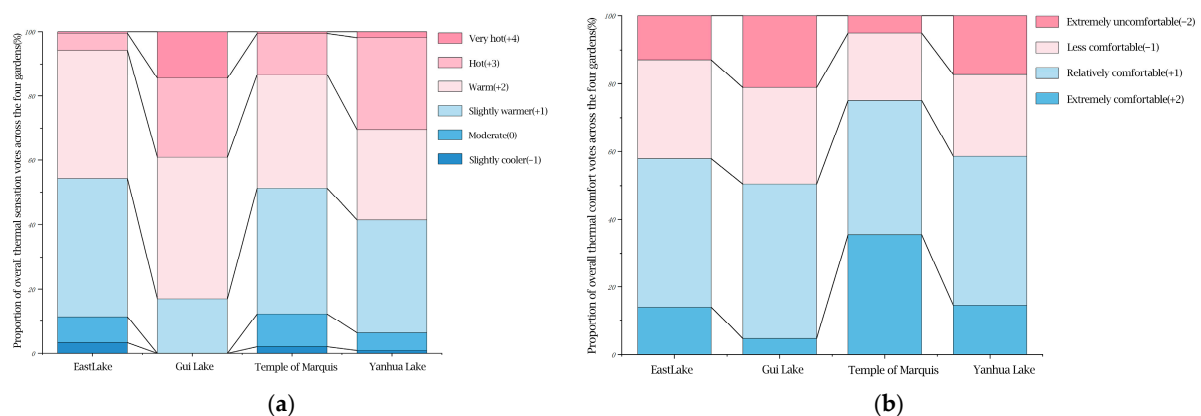


Figure 6. Percentage of thermal comfort in four parks: (a) Proportion of overall thermal sensation votes (TSV) across the four gardens. (b) Proportion of overall thermal comfort votes (TCV) across the four gardens.

Regarding thermal perception, the voting results for Gui Lake did not include the options “slightly cool” or “moderate.” Its “very hot” rating reached 14%, 13 percentage points higher than the other gardens, with extreme heat evaluations being particularly

prominent. Temple of Marquis recorded the highest proportion of “moderate” ratings at 10%, followed by East Lake at 8%, while Yanhua Pool registered only 5%. Both the Temple of Marquis and the East Lake showed less than 1% of extreme heat perception evaluations, indicating relatively stable conditions. In terms of thermal comfort, Gui Lake’s “very comfortable” rating was just 5%, significantly lower than those of the other three gardens, which ranged from 9% to 31%, revealing a marked disparity. This outcome is closely related to each garden’s spatial structure and landscape elements: Gui Lake has low canopy coverage from tall trees, limiting shading. Its large water bodies, which are interconnected throughout the garden, and the fact that over 80% of the surrounding architectural gray spaces are bordered by water on one or both sides, may intensify the effects of low canopy coverage by limiting shading and humidity, thereby increasing heat.

In contrast, the Temple of Marquis achieved the highest thermal comfort rating among the four gardens, with the largest proportion of “comfortable” responses. Its symmetrical layout and semi-open architecture facilitate air circulation and provide effective shading. Additionally, the garden features a high leaf area index and a dense vegetation canopy, which effectively reduces direct solar radiation and improves surface thermal equilibrium. The combined shading and ventilation effects of the vegetation and architecture significantly mitigate thermal loads in hot environments, thereby enhancing human thermal comfort.

3.1.2. Analysis of PET and Its Correlation with Thermal Comfort and Thermal Sensation in Celebrity Memorial Gardens in Xishu Region

Given the large sample sizes in the questionnaires collected in this study, the Shapiro–Wilk test indicated significant deviations from normality for both the thermal sensation and thermal comfort vote variables ($p < 0.001$). As a result, we decided against using the Pearson correlation coefficient, which requires normality, and instead chose the Spearman rank correlation coefficient for our analysis. This nonparametric test is better suited to our data because it does not assume normality and is more robust to skewness and outliers. Using this method, we could assess the correlation and validity between subjective and objective data. This analysis sets the stage for the next linear regression, which examines the relationship between PET data and subjective questionnaire responses across different measurement points, ultimately helping us establish thermal comfort thresholds within the Xishu celebrity memorial garden.

The obtained physiological equivalent temperature (PET) and subjective thermal comfort/sensation data (TCV, TSV) showed a strong positive correlation ($p < 0.01$). According to statistical correlation theory, the results are shown in Table 6. This suggests that within the architectural gray spaces of the celebrity memorial gardens in Xishu, higher PET is associated with higher thermal sensation and comfort scores. Notably, higher scores indicate greater discomfort and increased perception of heat.

Table 6. Correlation analysis between Physiologically Equivalent Temperature (PET) and Thermal Comfort and Sensation for four gardens.

		Gardens	Sample Size	TSV	TCV
PET	Spearman	East Lake	210	0.706 **	0.657 **
	Sig. (2-tailed)			<0.01	<0.01
	Spearman	Gui Lake	194	0.838 **	0.739 **
	Sig. (2-tailed)			<0.01	<0.01
	Spearman	Yanhua Lake	220	0.740 **	0.857 **
	Sig. (2-tailed)			<0.01	<0.01
	Spearman	Temple of Marquis	195	0.709 **	0.810 **
	Sig. (2-tailed)			<0.01	<0.01

** $p < 0.01$.

3.2. Identification of the Thermal Neutrality Threshold

Through a correlation analysis of subjective and objective data, this study systematically determined the thermal sensation thresholds for the gray spaces in the architectural structures of the Xishu Famous Figures Memorial Park. In thermal comfort research, linear regression is commonly used to quantify the relationship between the physiologically equivalent temperature (PET) and thermal sensation ratings. The PET threshold ranges obtained via linear regression are consistently narrower than those derived from the percentage-fit curve of thermal comfort ratings, indicating higher thermal comfort standards [52]. Furthermore, this method has been validated by previous scholars [59–61], which can directly reveal the marginal effects of environmental variables on thermal sensation, facilitating the derivation of thermal comfort thresholds and aligning with the analytical objectives of this study. Therefore, this study conducted regression analyses of Physiologically Equivalent Temperature (PET) and Thermal Sensation Voting (TSV) for each garden, followed by independent calibration of the thermal comfort thresholds. Before conducting the regression analysis, SPSS 27 was used to test for linearity, independence, and homoscedasticity. Due to the spatial proximity of the measurement points within the gardens, the residuals exhibited significant positive autocorrelation (Durbin–Watson = 0.567). To correct for the inferential bias caused by autocorrelation, this study further employed a linear mixed model, treating the measurement-point cluster variable as a random intercept to account for spatial autocorrelation. After correction, the effect of the core independent variable, TSV, on PET remained highly significant. The results showed that the influence of Thermal Sensation Vote (TSV) on Physiological Equivalent Temperature (PET) remained highly significant ($p < 0.001$), consistent with the original linear regression analysis.

To further elucidate the intrinsic relationship between human thermal sensation and thermal comfort within the studied environment, this research conducted supplementary quantitative analyses utilizing preliminary questionnaire data. Initially, PET (Physiological Equivalent Temperature) and TSV (Thermal Sensation Vote) data corresponding to the specific times and locations of each questionnaire were extracted for regression analysis to identify PET values associated with distinct thermal sensation levels. Under conditions of perfect stability, thermal neutrality is generally aligned with thermal comfort. Nevertheless, individuals exhibit adaptive responses through self-regulation mechanisms under varying climatic conditions, which may lead to deviations from this alignment. Prior studies have demonstrated that the range of temperatures perceived as comfortable and preferred by humans is relatively broad [54–56]. During data processing, the six-point thermal sensation scale, ranging from “slightly cool” to “very hot,” was numerically coded as -1 , 0 , $+1$, $+2$, $+3$, and $+4$, respectively. Similarly, the four-point thermal comfort scale, spanning from “very comfortable” to “extremely uncomfortable,” was assigned values of $+2$, $+1$, -1 , and -2 , respectively.

A regression analysis was performed to examine the relationship between the TSV collected via questionnaire ($n = 819$) and the corresponding physiologically equivalent temperature (PET). The findings are presented in Figure 7 (Regression analysis between TSV and PET across the four gardens. The dashed lines on the y-axis represent the TSV levels). The linear regression model produced a coefficient of determination (R^2) of 0.592.

Under conditions of absolute stability, it is generally accepted that thermal sensation and thermal comfort are correlated; that is, the thermal sensation at the point where one feels comfortable and the point where one wishes the temperature to remain constant is precisely neither too cold nor too hot. However, under different climatic conditions, individuals rely on their own regulatory mechanisms to achieve adaptation. The process of adapting to the environment often leads to a certain degree of deviation in this correspondence. Research has already shown that the range within which the human body feels comfortable,

corresponding to the desired constant temperature, is relatively broad. To further clarify the relationship between thermal sensation and thermal comfort in architectural gray spaces, a more in-depth analysis of the questionnaire results was conducted.

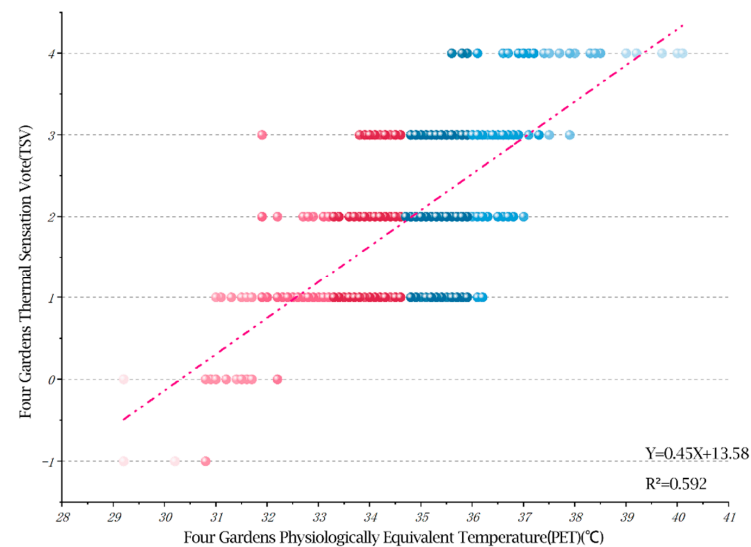


Figure 7. Regression analysis between thermal sensation vote (TSV) and physiologically equivalent temperature (PET) across the four gardens.

A Fitting thermal comfort and thermal sensation ($R^2 = 0.983$) results in a TSV of 0.577 when the TCV is 0 (Figure 8). Based on calculations using RayMan software, the Physiologically Equivalent Temperatures (PET) corresponding to each thermal sensation level—from slightly cool to very hot—were determined, and the four gardens were analyzed separately. The results showed that the thermal sensation deviation linked to the Thermal Comfort Vote (TCV) was approximately ± 0.6 . Therefore, the thermal sensation values were adjusted by ± 0.6 and plugged into the equation to redefine the PET threshold range for the thermal sensation in architectural gray spaces of the Xishu celebrity memorial garden during summer (Table 7). A comprehensive analysis indicates that the PET range associated with moderate human thermal sensation in the study area is 29.1–31.5 °C, with a thermal neutral temperature of 30.2 °C. This thermal neutral threshold is notably higher than the classic PET thermal comfort classification standard proposed by Matzarakis et al., and compared to PET thermal neutral temperatures in Singapore, Munich, Germany, and other climatic regions of China [59,61–63]. The thermal neutral temperature in the Xishu region is 0.5–1.5 °C higher. This suggests that visitors to the Xishu celebrity memorial gardens have greater thermal adaptability and heat tolerance. As a result, during summer, when $PET \leq 31.5$ °C, shaded areas of the memorial garden architecture in Western Shu can promote a moderate thermal sensation, offering effective thermal comfort for visitors.

Table 7. Thresholds of physiologically equivalent temperature (PET) corresponding to different summer thermal sensations in the gray spaces of Xishu celebrity memorial gardens.

Thermal Sensation	East Lake		Gui Lake		Temple of Marquis		Yanhua Lake		Four Gardens	
	Neutral Temperature	Threshold Range	Neutral Temperature	Threshold Range	Neutral Temperature	Threshold Range	Neutral Temperature	Threshold Range	Neutral Temperature	Threshold Range
Slightly cool	28.3	≤ 29.6	29.7	≤ 30.6	28.2	≤ 29.3	28.1	≤ 29.2	28	≤ 29.3
Moderate	30.9	29.6–32.2	31.4	30.6–32.3	30.4	29.3–31.5	30.2	29.2–31.3	30.2	29.3–31.5
Slightly warm	33.5	32.2–34.7	33.2	32.3–34	32.6	31.5–33.7	32.3	31.3–33.4	32.4	31.5–33.7
Warm	36.0	34.7–37.3	34.9	34–35.8	34.8	33.7–35.8	34.4	33.4–35.4	34.6	33.7–36
Hot	38.6	37.3–39.9	36.6	35.8–37.5	36.9	35.8–38	36.5	35.4–37.5	36.8	36–38.2
Very hot	41.2	> 39.9	38.3	> 37.5	39.1	> 38	38.6	> 37.5	39	> 38.2

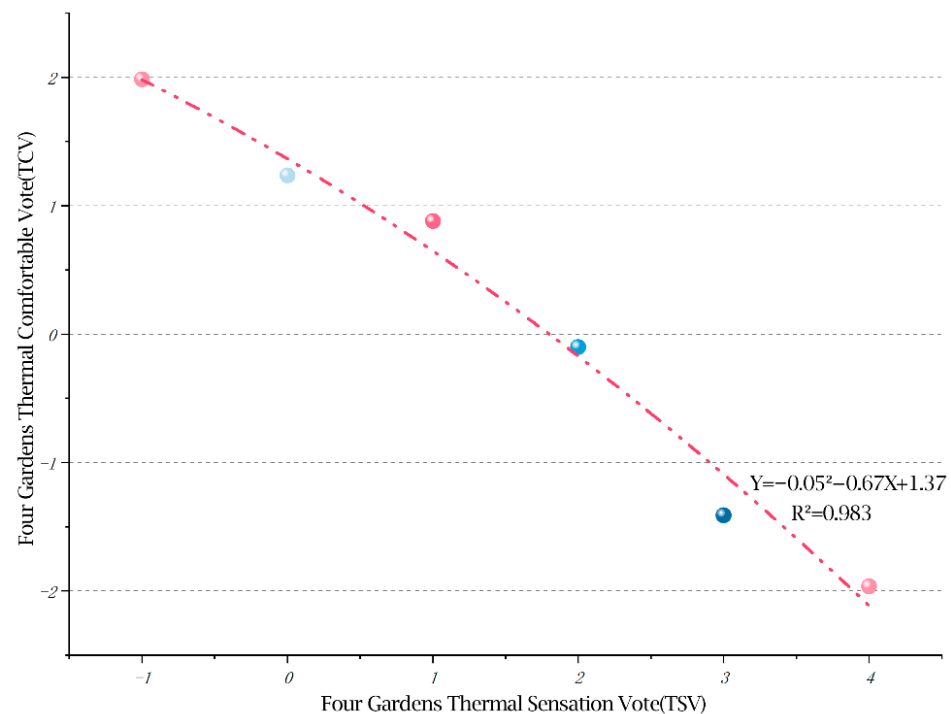


Figure 8. Scatter plot with fitting formula illustrating the correspondence between thermal sensation vote (TSV) and thermal comfort vote (TCV) across the four gardens.

3.3. Assessment and Categorization of Thermal Comfort in Architectural Gray Spaces Integrating Subjective and Objective Parameters

By combining the previously collected objective field data with subjective questionnaire responses, a calibration analysis was conducted to assess thermal comfort in architectural gray spaces. The study revealed that visitors in the Chengdu area can maintain a high level of thermal comfort even when experiencing a “slightly warm” thermal sensation. Accordingly, the range of “slightly cool” to “slightly warm” (28–32.4 °C) is defined as the acceptable thermal sensation range, while “warm,” “hot,” and “very hot” (34.6–39 °C) are categorized as unacceptable thermal sensation levels. Using this standard, along with the physiological equivalent temperature (PET) of different architectural gray space types and their corresponding measurement points, the study systematically analyzed differences in thermal comfort between various spaces and outdoor environments. This enabled the identification of which landscape elements, when integrated into specific architectural gray space types, can more effectively enhance human thermal comfort, thereby providing a foundation for optimizing landscape microclimate design.

By classifying and organizing measurement point data, with 32.4 °C established as the Physiological Equivalent Temperature (PET) threshold, the nine measurement points below this value are mainly spread across Donghu Lake, Yanhua Lake, and the Temple of Marquis. These areas show significant effectiveness in moderating the microclimate and lowering perceived temperature, thus improving human thermal comfort (Table 8). The following sections will review each type in turn.

Within the semi-enclosed areas of hybrid pavilion structures, four valid thermal sensation measurement locations were identified: E14, M6, Y5, and Y7. Canopy coverage in these garden zones ranged from 55.77% to 75.45%, while water features accounted for 24.3% to 26.17% of the total area. These findings suggest that this particular zone plays a significant role in enhancing human thermal comfort. The spatial layout of these areas features a point-like arrangement with open sides, which promotes cross-ventilation, enhances sweat evaporation, and supports convective heat dissipation. However, the

openness of these sides also exposes the spaces to lateral and ground-reflected radiation. In hybrid settings, the canopy of tall trees provides secondary overhead shade, effectively reducing multidirectional radiant heat exposure. At the same time, water bodies, due to their high specific heat capacity and slow rate of temperature rise, help cool the environment through evaporation. The combined effects of vegetative shading and evaporative cooling from water features significantly lower the mean radiant temperature, creating a thermally comfortable resting environment with minimal radiant heat exposure.

Table 8. Classification of monitoring point types and thermal comfort categories in Xishu Celebrity Memorial Gardens.

Type	Plant-Dominanted	Water-Dominanted	Hybrid
Gazebo	E1, E3, E7, E17 M7 Y3, Y4, Y14 G10, G11, G12	G6, G8, G14 Y13	E13, E14 M3, M6 Y5 , Y7, Y6
Corridor	E6 M5, M11, M12 Y2, Y8	G13	E8 G2, G3 M4 Y10
Bower		E10, E13 G5, G7, G9, G15 M8, Y12	E9 G4 Y9, Y11
Open halls	M1, M2, M9 , M10 Y1		

The bold measurement points indicate more comfortable positions.

Within plant-dominated architectural gray spaces featuring covered walkways, three acceptable thermal sensation measurement points were identified, all situated within the Temple of Marquis. The canopy coverage rates at these locations ranged from 39.86% to 49.77%. Each site was characterized by semi-open, partially enclosed structures, suggesting that higher canopy cover does not necessarily create optimal conditions in such environments. Excessive canopy coverage may hinder ventilation in walkways, thus reducing thermal comfort and increasing thermal discomfort. In vegetation-rich settings, plants mainly cool through transpiration, which releases moisture and absorbs latent heat, providing cooling effects with only slight increases in ambient humidity. This mechanism avoids the high-humidity stagnation issues often linked with water evaporation in hybrid environmental setups. The resulting humidification effect remains moderate, facilitating convective heat dissipation without significantly raising air humidity. As a result, this process effectively reduces the feeling of stuffiness caused by impaired sweat evaporation in high-humidity conditions, thereby enhancing thermal comfort.

Within architectural gray spaces characterized by open-hall designs dominated by plant elements, two suitable locations for thermal sensation monitoring have been identified at the Temple of Marquis, corresponding to garden canopy densities of 41.81% and 59.76%, respectively. These spaces are typically defined by semi-open structures with dual-sided transparency and clearly oriented ventilation axes, which facilitate the formation of cross-flow air currents. When positioned along the garden's central axis, these spaces often connect with the broader wind corridor system, serving as convergence points for airflow. Their semi-enclosed interfaces create a well-defined spatial domain that, together with vegetation such as tree branches and foliage, enhances enclosure and privacy. This combination fosters a strong psychological sense of shelter for users. As a result, this spatial setup effectively balances ventilation efficiency with environmental comfort.

3.4. Analysis of Landscape Elements and Thermal Comfort

After determining the thermal comfort thresholds for the celebrity memorial gardens in Xishu, the subsequent analysis employs correlation and quadratic regression analyses to further investigate the relationships between garden elements and human thermal comfort.

3.4.1. Correlation Analysis Between Physiological Equivalent Temperature (PET) and Landscape Factors

The results of the correlation analysis (Table 9) show that both vegetation canopy cover and water surface area are negatively correlated with PET, indicating they help reduce perceived heat and improve comfort. Specifically, the negative correlation between vegetation canopy cover and PET was statistically significant at the 0.01 level and was much stronger than that with water body area. Yanhua Lake and Temple of Marquis, which have relatively small water bodies, showed a negative correlation trend, while Gui Lake and East Lake, with larger water bodies, tended to increase temperature and humidity, resulting in a positive correlation trend; however, neither reached statistical significance. The Sky Visibility Factor (SVF) showed a significant positive correlation with PET: the higher the SVF, the higher the PET and the worse the thermal comfort; conversely, lower SVF values were associated with lower PET. In summary, more vegetation canopy cover and lower SVF lead to lower Physiological Equivalent Temperature (PET) and better thermal comfort. These findings reveal only statistical relationships among variables and do not indicate direct cause-and-effect; further research is needed to understand the underlying mechanisms.

Table 9. Correlation analysis between physiologically equivalent temperature (PET) and landscape for four gardens.

		Gardens	Canopy Coverage	Percentage of Water Area	SVF
PET	Spearman	East Lake	−0.283 **	0.018	0.284 **
	Sig. (2-tailed)		0.002	0.847	0.002
	Spearman	Gui Lake	−0.330 **	0.072	0.385 **
	Sig. (2-tailed)		<0.01	0.419	<0.01
	Spearman	Yanhua Lake	−0.282 **	−0.118	0.273 **
	Sig. (2-tailed)		0.002	0.199	0.003
	Spearman	Temple of Marquis	−0.361 **	−0.040	0.376 **
	Sig. (2-tailed)		<0.01	0.971	<0.01

** $p < 0.01$.

3.4.2. Secondary Regression Analysis of Physiological Equivalent Temperature (PET) and Landscape Factors

A correlation analysis examining the relationship between landscape elements and physiologically equivalent temperature (PET) across four gardens provided initial insights into the mechanisms behind this relationship. To quantify these connections and identify key thresholds, regression analysis was later applied. Using landscape parameter indicators within a 10 m radius of architectural gray spaces, regression models were built to relate element ratios to PET, yielding mathematical expressions that describe PET variations as a function of element composition. Due to notable differences in microclimate and element composition among the gardens, quadratic regression analyses were performed separately for each site. With model calculations and goodness-of-fit assessments, critical thresholds and optimal ranges for element ratios were identified for each garden, followed by a comprehensive integrated analysis. This research aims to offer quantitative design guidelines to improve thermal comfort in garden landscapes, thereby strengthening the scientific basis and practical effectiveness of landscape planning.

East Lake

Figure 9 shows that the coefficients of determination (R^2) for the relationships between physiological equivalent temperature (PET) and SVF, and between PET and plant canopy coverage, are 0.742 and 0.968, respectively, indicating strong model fits. Figure 9a reveals that PET increases with rising SVF, indicating that greater sky visibility is associated with higher PET. In contrast, Figure 9b shows a nonlinear relationship between plant canopy coverage around the East Lake gray space and PET: PET decreases significantly initially and then increases gradually. Quadratic regression identifies an inflection point at 83.73% canopy coverage. Within 0–83.73% coverage, PET decreases steadily ($\approx 0.6^\circ\text{C}$ per 10% increase), reflecting the cooling effect of plant shading and transpiration. At 83.73%, PET reaches its minimum of 34.48°C . Beyond this threshold, PET increases slightly, suggesting that excessive canopy coverage does not always improve environmental comfort.

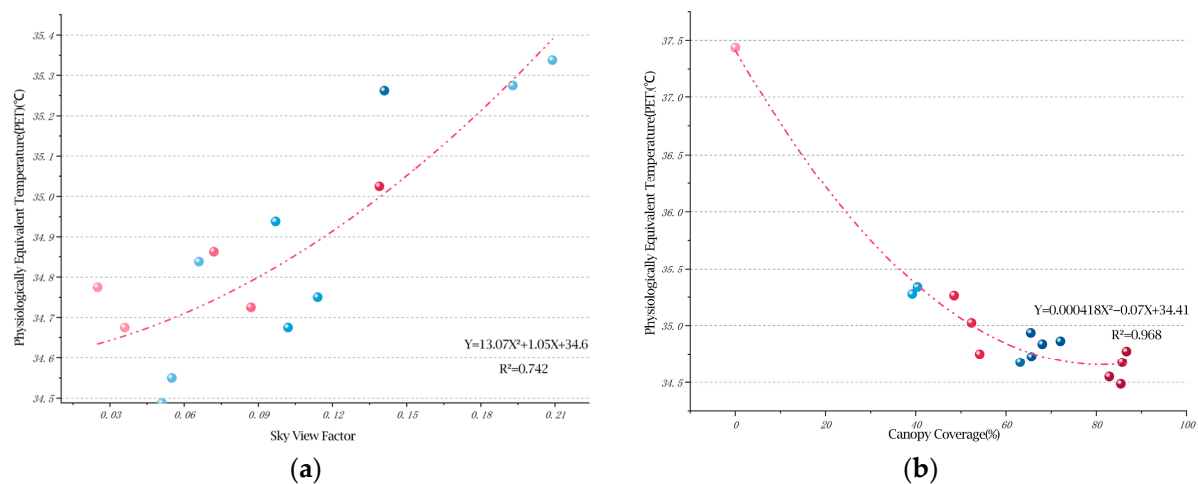


Figure 9. The relationship between PET and SVF and canopy coverage of East Lake: (a) SVF and PET; (b) canopy coverage and PET (the different colors of data points are only for visual differentiation and do not imply additional classification or meaning).

Because of canopy coverage and sky visibility, Table 8 shows a negative correlation between water bodies and PET values. Figure 10 shows that the water area ratio explains 56.8% of PET variation ($R^2 = 0.568$), with PET first decreasing and then gradually increasing. A binomial model identifies the inflection point at a water area ratio of 22.72%. Within 0–22.72% water coverage, PET drops steadily (about 0.2°C per 10% increase in water coverage). At 22.72% water coverage, PET reaches its lowest point at 34.6°C , indicating moderate heat stress. Beyond this point, PET stops decreasing and begins to rise gradually.

Gui Lake

Figure 11 shows the coefficients of determination (R^2) for the relationships between PET and SVF, and between PET and plant canopy coverage, which are 0.751 and 0.853, respectively, indicating a strong model fit. Figure 11a demonstrates that the positive correlation between SVF and PET remains consistent at Gui Lake and East Lake, as greater sky openness enhances surface exposure to solar and longwave radiation, thereby increasing PET. Figure 11b shows the relationship between canopy coverage and PET at Gui Lake, following the same trend as East Lake. The inflection point occurs at 54.87% canopy coverage: within 0–54.87%, PET decreases by approximately 0.8°C per 10% increase in coverage; at the inflection point, PET reaches its minimum of 35.2°C . Beyond 58.37% coverage, PET increases rather than decreases.

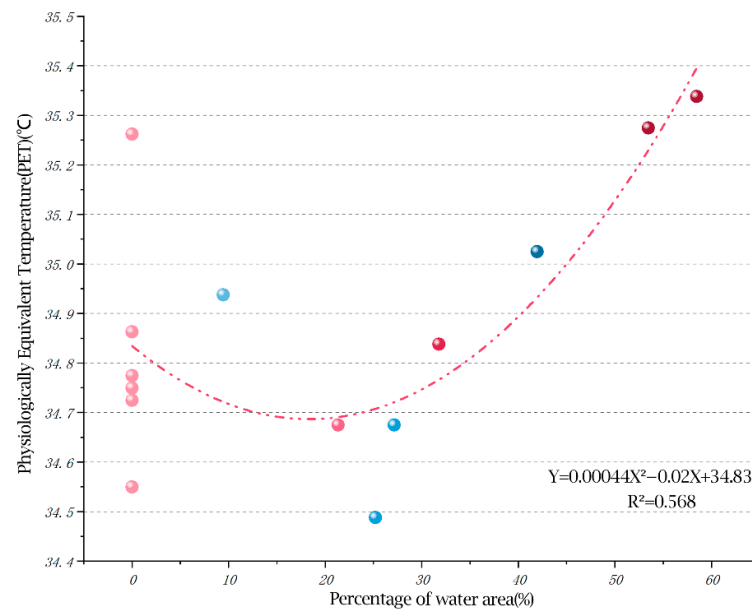


Figure 10. The relationship between PET and the water of East Lake.

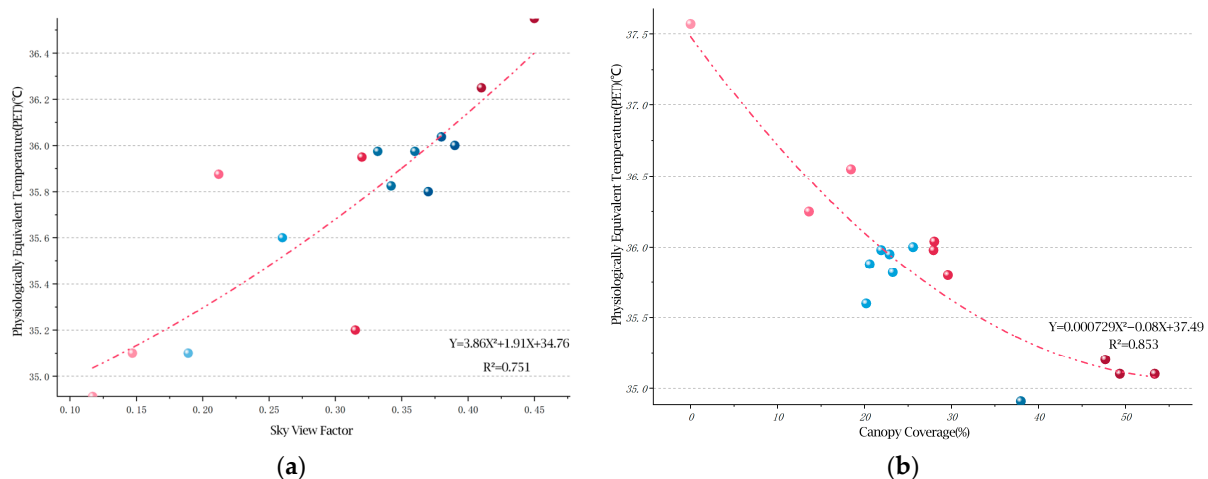


Figure 11. The relationship between PET and SVF and canopy coverage of Gui Lake: (a) SVF and PET; (b) canopy coverage and PET.

Significant differences exist in the critical values between Gui Lake and East Lake. Gui Lake has lower canopy coverage, mainly medium-sized trees with open canopies, and a larger water surface area; its extensive water bodies provide substantial evaporative cooling, which outweighs the cooling effect of sparse vegetation, leading to early saturation of the system's cooling capacity. In contrast, East Lake has dense, multi-layered vegetation with higher canopy coverage and smaller, localized water bodies. Without significant water-mediated cooling, its temperature and humidity reductions depend primarily on vegetation—dense canopy shading, and transpiration optimizes cooling potential, while PET stabilizes only when the canopy approaches full closure and the system reaches a stable state.

As illustrated in Figure 12, the relationship between water area proportion and PET has an R^2 of 0.548, showing an initial gradual decrease followed by a gradual increase. The inflection point is at a 21% water area proportion: when the proportion is 0–21%, PET decreases by approximately 0.2 °C for every 10% increase in water area; at 21%, PET reaches its minimum of 35.47 °C. Beyond 21%, PET no longer decreases; instead, it gradually increases.

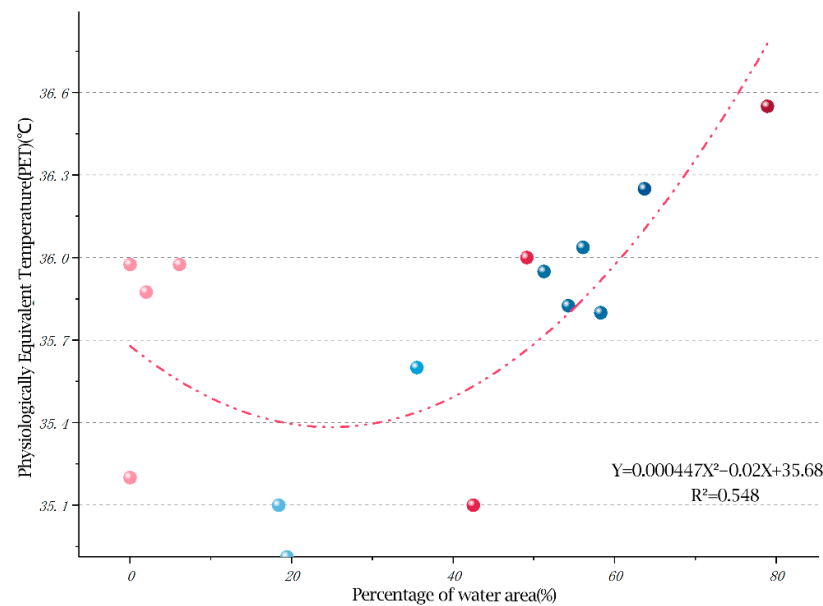


Figure 12. The relationship between PET and the water of Gui Lake.

Temple of Marquis

Figure 13 shows the coefficients of determination (R^2) for PET with SVF and plant canopy coverage at the Temple of Marquis, which are 0.88 and 0.881, respectively, indicating a strong model fit. Figure 13a demonstrates a positive correlation between SVF and PET at the Temple of Marquis. Figure 13b illustrates the relationship between canopy coverage and PET at the Temple of Marquis, aligning with trends observed in other garden environments: PET declines sharply initially and then increases, with an inflection point at 47.45% canopy coverage. Within the range of 0–47.45% canopy coverage, PET decreases by 1.3 °C for every 10% increase in canopy coverage (cooling effect of plants). At 47.45% canopy coverage, PET reaches its lowest point of 33.53 °C (slightly warm range).

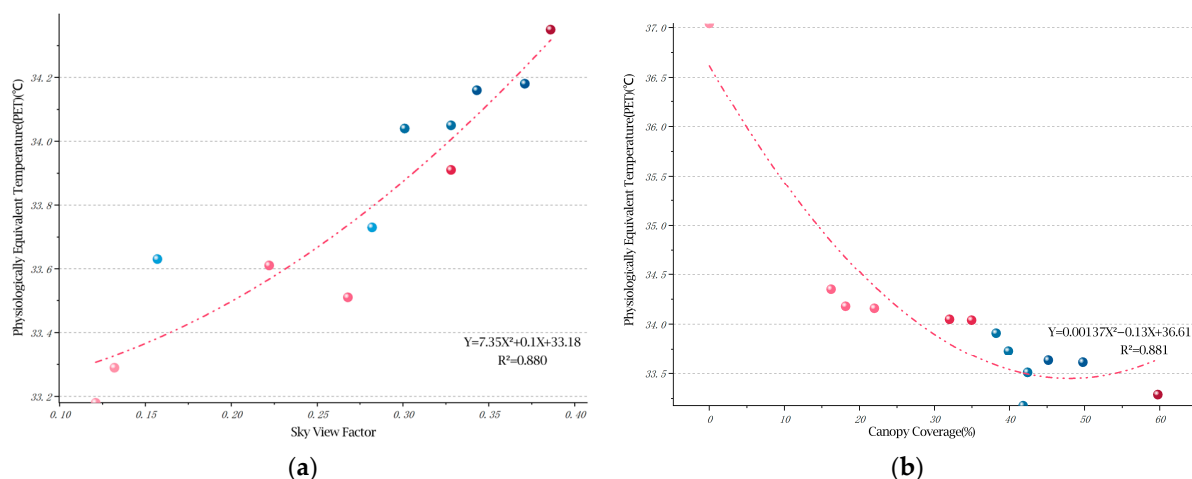


Figure 13. The relationship between PET and SVF and canopy coverage of the Temple of Marquis: (a) SVF and PET; (b) canopy coverage and PET.

A comparative analysis of four gardens shows that the Temple of Marquis has the lowest critical canopy coverage threshold at all measurement points. This is closely related to its spatial configuration, dominated by commemorative shrines and contiguous architectural structures. The gray spaces formed by pavilions, corridors, terraces, and their enclosed courtyards provide substantial shading. Before vegetation exerts a cooling effect, the architectural framework creates a “pre-shaded” environment in main pathways

and activity areas. This strategy, which relies on architectural shading to reduce sky view factor (SVF), lowers the need for vegetative shading. It reflects the ecological ingenuity of classical Chinese garden design—drawing on natural elements, integrating architecture and landscape to optimize microclimate, enhance thermal comfort, and achieve sustainable thermal regulation with minimal ecological input.

As shown in Figure 14, the relationship between water body proportion and PET has an R^2 of 0.223, indicating a relatively weak model fit. This low R^2 is mainly due to the highly uneven distribution of data points. However, at the few monitoring sites with water bodies, data points cluster closely around the fitted curve, suggesting a nonlinear relationship between the two variables within the observed range of water body proportions. The fitted curve shows that PET first decreases gradually and then increases, with the inflection point at a 13.72% water body proportion, where PET reaches its minimum of 33.59 °C. Beyond this point, PET stops decreasing and begins to rise slowly. Notably, the Temple of Marquis has the lowest critical water body proportion threshold. Its regular architectural layout partly compensates for the microclimate regulation usually provided by water bodies: dense building clusters and extensive gray spaces offer effective shading, reduce SVF and solar radiation heat, and slow airflow to maintain courtyard humidity. This existing humid microenvironment reduces the additional humidification effect of water bodies, thereby shifting the threshold at which the negative impacts of excessive water body proportion become apparent.

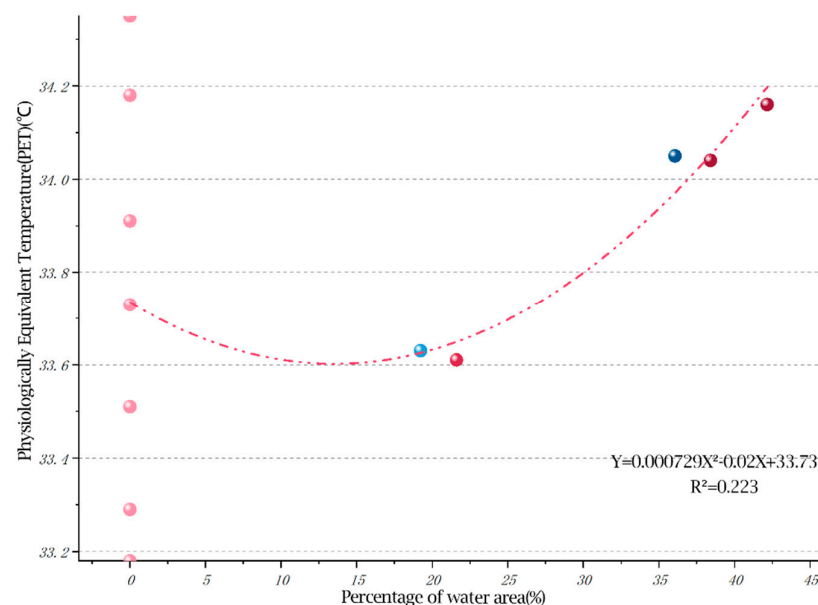


Figure 14. The relationship between PET and the water of the Temple of Marqui.

Yanhua Lake

Figure 15 shows the R^2 values of PET at different measurement points in Yanhua Lake: 0.789 (between PET and SVF) and 0.891 (between PET and plant canopy coverage), indicating a strong model fit. Figure 15a shows a positive correlation between SVF and PET. Figure 15b presents the relationship between canopy coverage and PET in Yanhua Lake, consistent with patterns in other gardens: PET first decreases sharply and then increases gradually. Quadratic regression identifies the inflection point at 64.21% canopy coverage. Within 0–64.21% canopy coverage, PET decreases consistently (≈ 0.8 °C reduction per 10% increase in canopy coverage), reflecting the cooling effects of plant shading and transpiration. At 64.21% coverage, PET reaches its minimum of 33.56 °C (warm thermal perception category). Beyond this threshold, PET no longer decreases but slightly rises.

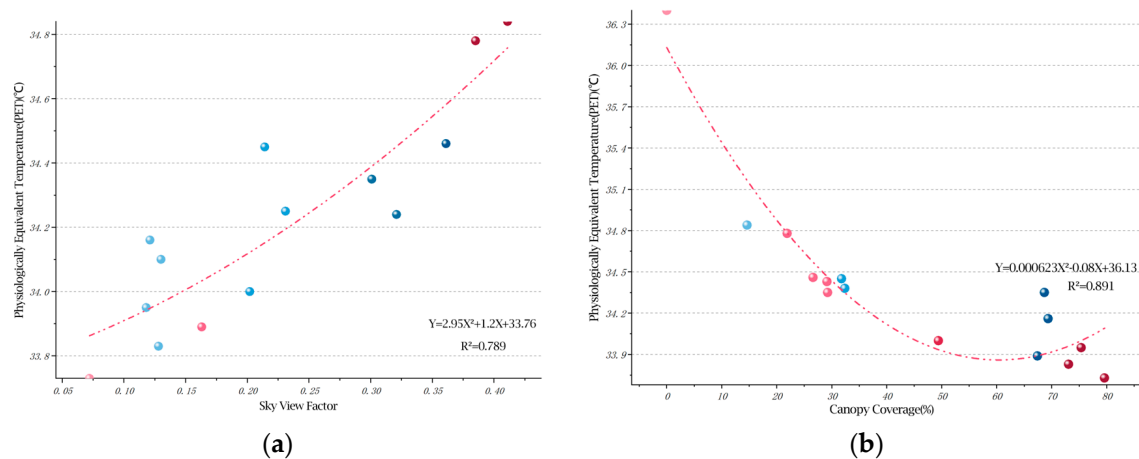


Figure 15. The relationship between PET and SVF and canopy coverage of Yanhua Lake: (a) SVF and PET; (b) canopy coverage and PET.

A comparative analysis of four gardens shows that Yanhua Lake's canopy coverage threshold is moderate among all measurement sites. Unlike the Temple of Marquis, which is dominated by formal architecture with vegetation hidden by built structures, Yanhua Lake's shade comes from a mix of dense buildings and courtyard trees. Its layout is divided by architectural features, with narrow alleyways limiting ventilation and airflow, resulting in lower wind speeds beneath the canopy. Yanhua Lake has separate areas (Confucian Temple, Yanhua Pond, Lu You Shrine), where the balanced combination of vegetation, water features, and architecture results in moderate canopy coverage thresholds and the lowest PET values in the garden.

As illustrated in Figure 16, the correlation between water area proportion and PET has a coefficient of determination (R^2) of 0.713, indicating an initial gradual decline followed by an increase. The inflection point of the fitted curve is at a water area proportion of 27.78%. Within a water area ratio of 0–27.78%, PET decreases continuously with increasing water coverage, with a 0.4 °C reduction in PET per 10% increase in water coverage. At 27.78% water area, PET reaches its minimum of 33.9 °C; beyond this threshold, PET stops decreasing and rises gradually.

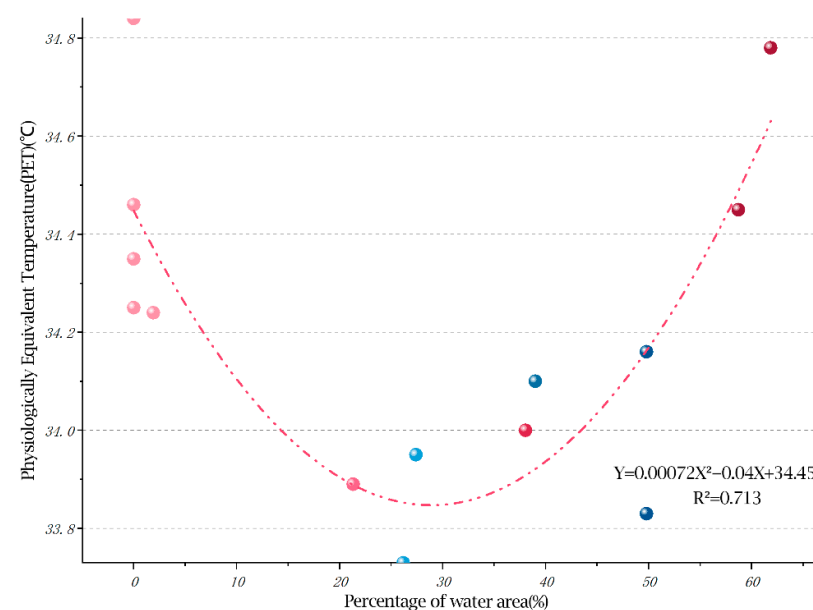


Figure 16. The relationship between PET and the water of Yanhua Lake.

Compared with other garden sites, Yanhua Lake has the highest critical threshold for water area proportion. Though it shares a central pond configuration with East Lake (a similarly designed garden), their critical thresholds differ significantly, due to differences in the microenvironmental structures around water bodies. East Lake's inkstone pond is surrounded by dense bamboo groves, forming a highly enclosed boundary layer that restricts air circulation and hinders the dispersal of cool air from water evaporation, so its thermal comfort relies more on vegetative shading. In contrast, Yanhua Lake's unique microenvironment enables its water bodies to better exert their regulatory function.

3.4.3. Assessment and Enhancement Methodologies

The study investigates thermal comfort in four types of gray spaces within Xishu gardens, revealing distinct characteristics and optimization strategies for each. In Gazebo spaces, hybrid environments combining vegetation and water bodies achieve the best comfort, with optimal plant canopy cover between 55.77% and 75.45% and water coverage around 24.3% to 26.17%. In contrast, spaces dominated solely by plants or water perform worse due to ventilation issues or excessive humidity. Recommendations for traditional gazebos include planting tall deciduous trees on the west and southwest sides and ensuring ground-level airflow. For water-dominated gazebos, installing fountains or misting systems and aligning with summer winds can enhance evaporative cooling. In Corridor spaces, the most comfortable points are plant-dominated, with a lower optimal canopy coverage of 39.86% to 45.16%. Strategies involve reducing the sizes of adjacent water bodies, maintaining this canopy threshold, and pruning vegetation to create ventilation channels aligned with prevailing summer north winds. For Bower spaces, all surveyed points are either water-dominated or hybrid, with PET values exceeding 33.7 °C, indicating severe discomfort due to lack of shade and poor ventilation. Optimization focuses on adding retractable awnings, ecological floating islands, and replacing solid platforms with grating to improve airflow. Finally, Open Halls exhibit the highest thermal comfort levels, attributed to their semi-open design and balanced canopy coverage of 41.81% to 59.76%. Strategies include strategic plant placement to manage humidity and the use of low-velocity ceiling fans during low-wind periods. Overall, a balanced integration of vegetation, water features, and targeted ventilation is critical for improving thermal comfort across these gray spaces.

4. Conclusions, Discussion and Limitations

4.1. Conclusions and Discussion

This study examines typical memorial gardens on the Chengdu Plain that honor renowned figures of ancient Xishu: East Lake, Gui Lake, Temple of Marquis, and Yanhua Lake. It analyzes the thermal environment and human thermal comfort in these gardens' architectural gray spaces during the humid summer season. By integrating objective environmental measurements, subjective questionnaire surveys, and quantitative statistical analysis, the study systematically examines how garden elements and gray space morphology influence thermal comfort. It further establishes the physiological equivalent temperature (PET) threshold range for summer thermal comfort within these gray spaces.

The main findings are as follows: (1) Gray spaces within the Xishu Celebrity Memorial Gardens show significant effects on microclimate regulation. Compared to external control sites, summer air temperatures in these gray spaces dropped by an average of 0.8 to 4.3 °C, and relative humidity increased by up to 2.2–22.33%, and PET values decreased by about 31 °C. This is consistent with previous findings by scholars regarding the influence of garden elements on mechanisms regulating microclimate [26–28]. These results highlight the critical role of vegetation and water features in cooling, humidifying, and enhancing thermal comfort [59]. (2) Differences in spatial types and element arrangements notably

influence thermal comfort. Open halls provide ideal thermal conditions due to their high sense of enclosure and effective shading, while gazebos, which are more open, exhibit greater thermal variation and rely more on nearby elements. Corridors and bower spaces benefit from combined ventilation and shading, demonstrating that semi-open gray spaces provide good shading but still face ventilation challenges, supporting earlier research [58]. (3) The layout of surrounding landscape elements within gray spaces profoundly affects thermal comfort. Areas that feature mainly plants or a mix typically achieve better comfort than those dominated by water features. Plant areas reach optimal shading and transpiration when canopy coverage is between 40% and 70%, though thresholds may vary with local conditions. Water-dominated zones often cause discomfort due to high humidity and poor ventilation. This is consistent with the results of previous scholars' simulation studies [31]. However, hybrid systems optimize comfort when canopy coverage is between 50% and 60% and water coverage is between 20% and 30%, leveraging the beneficial "blue-green" synergy [51,57]. Excessive domination by a single element reduces comfort, while balanced mixes effectively regulate shading, evaporation, and airflow. (4) Residents in Western Sichuan show strong thermal adaptability. Surveys reveal that while "warm" sensations were most common (36.6%), "relatively comfortable" responses accounted for 43.47%, indicating that pedestrians can remain comfortable even outside the thermal neutrality zone. This demonstrates the physiological and psychological adaptation of locals to the humid-hot climate. (5) Regression analysis of PET and TSV data shows that the PET neutral temperature range for a "moderate" summer thermal sensation across the four gardens is between 30.9 °C and 31.4 °C, with a PET comfort threshold of 29.6 °C to 33.0 °C. Compared to Lingnan gardens, this region experiences smaller fluctuations and lower maximum PET values, offering a scientific basis for improving microclimate design in garden environments.

This research investigates celebrity memorial gardens in Xishu, with an emphasis on their environmental adaptability to the region's hot and humid climate. It addresses a persistent gap in classical garden studies, which have historically concentrated on predominant garden styles from Jiangnan, Northern China, and Lingnan regions. By systematically categorizing the gray spaces within garden architecture, the study identifies four structural typologies: gazebos, corridors, bowers, and open halls. These are further analyzed alongside three landscape element configurations—plant-dominant, water-dominant, and hybrid—yielding a more nuanced typological framework.

Building upon this framework, the study integrates both objective and subjective data to construct a regression model correlating Physiological Equivalent Temperature (PET) with Thermal Sensation Vote (TSV). It methodically establishes a PET threshold range indicative of thermal comfort during summer within garden gray spaces in the Western Sichuan region. This provides empirically grounded and practical technical guidance for assessing thermal environments and optimizing garden landscape design in comparable climatic contexts.

This study systematically examines the environmental adaptability of memorial gardens dedicated to renowned figures in Western Shu under humid, hot conditions, filling a gap in microclimate research on classical Chinese memorial gardens in this region. By categorizing architectural gray spaces into four types—Gazebo, Corridor, Bower, and Open halls—and integrating three landscape configuration types—plant-dominated, water-dominated, and hybrid—a refined typological research framework was established. Based on objective and subjective field measurements, regression models linking Physiologically Equivalent Temperature (PET) and Thermal Sensation Voting (TSV) were developed. This research first proposes the PET thermal comfort threshold range for garden gray spaces in Western Sichuan during summer, providing quantitative evidence for thermal environment

assessments in gardens within similar climatic zones. By quantifying indicators such as plant canopy closure, water area proportion, and sky visibility factor (SVF), regression analysis revealed the “optimal range” for plant and water configuration, transcending traditional empirical understandings of linear relationships. Empirical data validated the ecological wisdom of microclimate regulation in West Shu’s memorial gardens, advancing the integration of traditional garden design principles with modern climate-adaptive design. This research effectively fuses traditional horticultural philosophy with contemporary environmental science.

4.2. Limitation

Nonetheless, the study has certain limitations. It focuses only on four celebrity memorial gardens in Chengdu, which, although representative, do not cover the full variety of garden types within the Xishu. Future research should consider expanding the sample to include more regions and different types of gardens to improve the generalizability of the results. The study focuses only on thermal comfort during humid summer conditions, without comparing it with other seasons such as spring, autumn, or winter. Future studies could use continuous, year-round, or multi-seasonal monitoring to explore how garden gray spaces regulate climate and how people adapt during different seasons. Methodologically, even with a large questionnaire sample size ($n = 819$), fully reducing individual differences in thermal comfort assessments remains difficult. Future research might include physiological measurements—such as skin temperature and heart rate variability—to better link subjective evaluations with objective data, including factors like clothing insulation, activity levels, and psychological expectations. Finally, although initial evidence indicates a synergistic effect between vegetation and water bodies, further research using numerical simulations and other analytical methods is needed to clarify the underlying mechanisms. Additionally, the rigor of this study could be strengthened by expanding the scope to compare identical areas of green space and water bodies within the same urban environment.

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Abbreviations

The following abbreviations are used in this manuscript:

PET	Physiological Equivalent Temperature
MRT	Mean Radiant Temperature
SVF	Sky View Factor
TCV	Thermal Comfort Vote
TSV	Thermal Sensation Vote

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