atmosphere

Article

Study on Strategy for Optimization of Thermal Comfort of College Courtyards in Lingnan Area in Summer

Yiqi Tao [1,2,3], Yiyun Lou [2], Zebin Chen [2], Fangyuan Zhao [2], Weijen Wang [4,*] and Xiaoyu Lin [5,*]

1 Shenzhen Key Laboratory of Architecture for Health and Well-Being (in Preparation), Shenzhen University, Shenzhen 518060, China; taoyiqi@szu.edu.cn
2 School of Architecture and Urban Planning, Shenzhen University, Shenzhen 518060, China; 2210325067@email.szu.edu.cn (Y.L.); 2210325065@email.szu.edu.cn (Z.C.); 2210325063@email.szu.edu.cn (F.Z.)
3 Center for Human-Oriented Environment and Sustainable Design, Shenzhen University, Shenzhen 518060, China
4 Faculty of Architecture, The University of Hong Kong, Hong Kong 999077, China
5 School of Architecture, Harbin Institute of Technology, Shenzhen 518055, China
* Correspondence: wjwang@hku.hk (W.W.); linxiaoyu@hit.edu.cn (X.L.)

Abstract: The campus courtyards in the Lingnan area are commonly used spaces. Therefore, their thermal comfort is highly important for improving user satisfaction. This study conducted field research on 18 courtyards in four universities in Lingnan to explore the effects of their architectural design factors on the thermal environment. Relevant studies have proved that courtyards are cost-effective in microclimate regulation, and individual factors such as the scale and openness of the courtyards have also been shown to have an effect on the thermal comfort of the courtyards. This study synthesizes multidimensional architectural design factors to explore and analyze the thermal environments of college courtyards. Physiologically equivalent temperature (PET) is selected as the thermal comfort evaluation index for the study and the conclusions are as follows: (1) The thermal environment is the most important factor influencing visitors to the courtyards (22%), and good thermal comfort improves the efficiency of using the college courtyards; (2) the courtyards have a positive microclimate regulating function, and a cooling effect occurs in 80% of them; and (3) the floor location, type, orientation, and sky view factor (SVF) of the courtyards are the main design factors affecting the thermal environment and PET. The first three factors were negatively correlated with PET ($p < 0.05$),and SVF was positively correlated with PET ($p = 0.651$). Passive courtyard design strategies are presented based on the findings of this study.

Keywords: Lingnan area; universities; courtyards; thermal comfort; design strategies

check for updates

Citation: Tao, Y.; Lou, Y.; Chen, Z.; Zhao, F.; Wang, W.; Lin, X. Study on Strategy for Optimization of Thermal Comfort of College Courtyards in Lingnan Area in Summer. *Atmosphere* **2023**, *14*, 1685. https://doi.org/10.3390/atmos14111685

Academic Editor: Giridharan Renganathan

Received: 10 October 2023
Revised: 1 November 2023
Accepted: 4 November 2023
Published: 14 November 2023

1. Introduction

Lingnan is situated in an area with hot summers and warm winters, as well as high humidity, copious rainfall, frequent typhoons, and powerful sun radiation [1]. People are vulnerable to the impacts of hot and humid weather in these climates, which can result in discomfort and negative emotions. Traditional Lingnan architecture frequently incorporates combinations of patios, open halls, and courtyards, which has been found to be successful in controlling the microclimate with low economic cost [2]. The design of courtyards has drawn particular attention in recent years [3]. By improving the physical environment of the courtyard and lowering the heat island effect through rational design, it is possible to improve thermal comfort [4].

Recent studies on courtyards and their thermal environment have demonstrated their ability to provide a cool microclimate in the summer [5,6], especially in hot and humid regions [7]. Diz-Mellado et al. [8] used thermal comfort modeling to highlight the thermal performance and usability of courtyards in hot climates and demonstrated how courtyards are used to promote thermal comfort in large spaces by casting shadows. Meanwhile, Callejas et al. [9] found that courtyard design had a passive cooling impact on internal and external courtyards. Tafti et al. [10] concluded that sunken courtyards could offer comfortable temperatures, thereby increasing attention and creativity throughout the summer. Finally, Li et al. [11] demonstrated that trees performed best in terms of enhancing thermal comfort in courtyards by simulating the impact of four different natural elements (trees, bushes, grass, and water) on heat dissipation.

Many studies have focused on the design factors that have impacted the thermal environment. For instance, regarding courtyard size, Callejas [12] demonstrated that deep courtyards are more effective at cooling. Other researchers have measured the courtyard aspect ratio; for example, Meng et al. [13] demonstrated that an atrium courtyard with a 1:2 aspect ratio offers a more stable and generally agreeable internal thermal environment in a hot, humid basin area, while Li Yang [14] stated that ventilation and air quality are at their finest when the aspect ratio is 1:2. Regarding openness of courtyards, some studies [15,16] have found spaces with a higher degree of enclosure to be more tolerant to climate change. Daramola et al. [17] examined the thermal characteristics of urban surfaces and discovered that areas with higher sensible heat fluxes (H) and higher land surface temperature (LST) also have higher SVF. Regarding orientation of courtyards, Yazdi et al. [18] extracted the properties of courtyards using deep learning and investigated how the orientation of courtyards affects their climate. Qiao Zhengjun [19] demonstrated that it is optimal to prioritize courtyard designs with a north, east, and south orientation in hot summer/cold winter areas and hot summer/warm winter areas. Regarding courtyard components, the placement of green water features has been found to have a particularly high impact on the thermal environment, and greening can effectively lower the temperature, especially in the summer. Finally, regarding paving, Jiayu et al. [20] found that grass paving significantly decreased the ground and surface temperature of the nearby buildings compared to asphalt paving; the type of paving was also found to impact the temperature of the courtyard itself.

In short, researchers have recently begun to focus on the impact of design factors on physiological equivalent temperature (PET) in such places as squares and streets [21,22]. Studies found that microclimate and PET are improved by various elements (e.g., water and plants) [23], SVF and PET are positively correlated in private outdoor spaces [24], and the type of paving influences diverse green space settings [25].

According to the literature, few studies have used PET to measure thermal comfort in courtyards, and most have only discussed individual design factors that influence the thermal environment. This study will categorize courtyards in colleges and universities in the Lingnan area, consider and quantify diverse and complex spatial elements such as scale, orientation, landscape features, etc., in terms of multidimensional architectural design factors, and examine the impact of various architectural design factors on the thermal environment and PET value to validate and further supplement and enrich the conclusions of previous researchers' single-factor studies of thermal environments affecting ensemble spaces. The purpose of this study is to improve the thermal comfort and usage of the existing courtyards in the Lingnan area, and to offer design guidelines for such spaces.

2. Methods

2.1. Study Sites

A total of 18 courtyards in 7 representative campus buildings of 4 contemporary campuses in the Lingnan area (namely, Lingnan University (Hong Kong), Hong Kong Polytechnic University (Hong Kong), Dongguan Taiwanese School (Dongguan), and The Chinese University of Hong Kong (Shenzhen)) were chosen as research subjects based on previous research on the thermal comfort of courtyards. In accordance with varying floor locations, the courtyards examined in this study were divided into five different types: connecting courtyard, atrium, roof terrace, sky garden, and skylight courtyard (Figure 1).

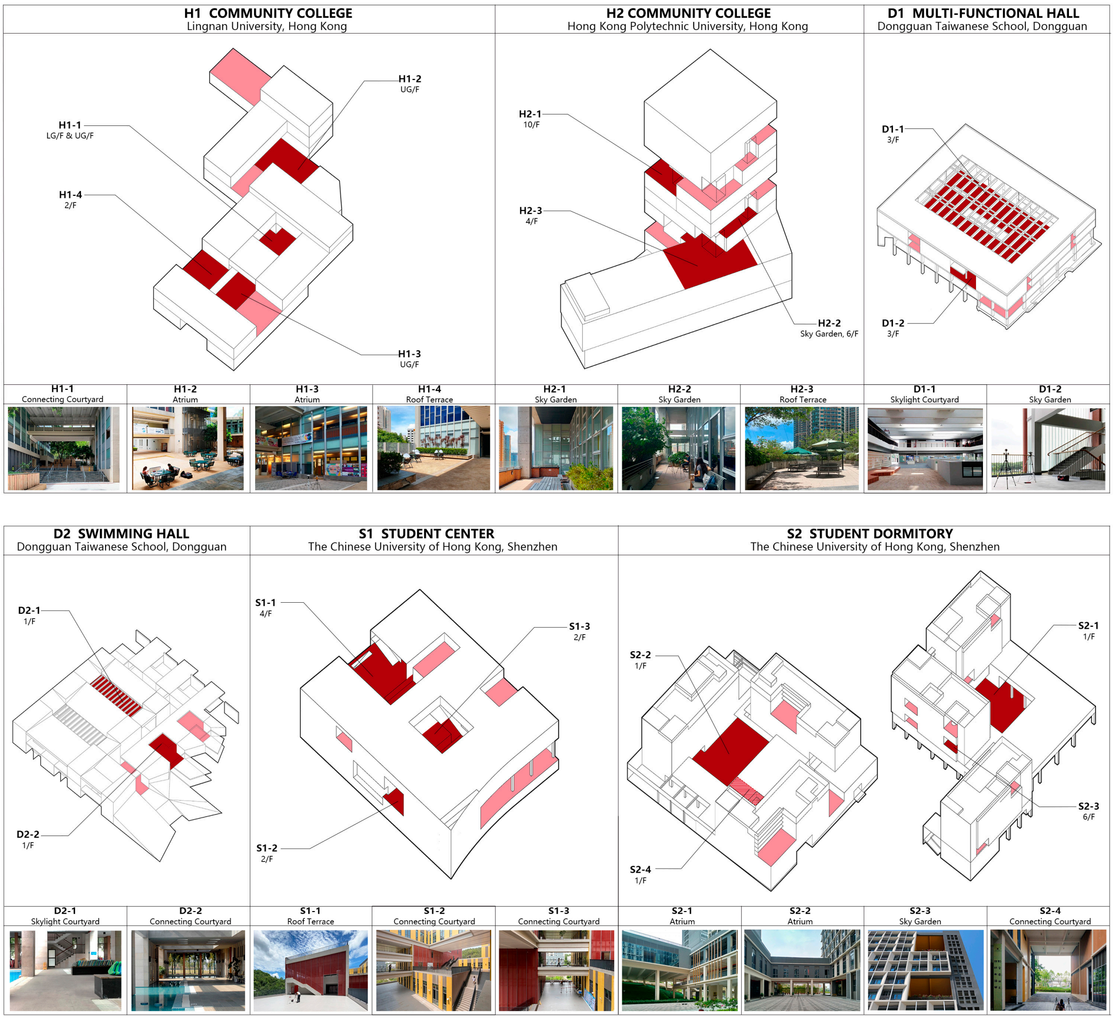


Figure 1. Basic information on the university courtyards examined.

1. Community College Lingnan University, Hong Kong (H1)

This site is situated on the northeastern side of Lingnan University, which has used building blocks to create several courtyards at the community college. Four courtyards were selected in this study: Courtyard 1, a connecting courtyard at the entry and exit of the building that, according to the grand staircase's layout, connects to the campus road; Courtyards 2 and 3, both of which are atriums and sunken courtyards; and Courtyard 4, which is a roof terrace located above the classrooms.

2. Community College—Hong Kong Polytechnic University, Hong Kong (H2)

Three courtyards at the community college were chosen for investigation, all of which were set up to accommodate vertical traffic. Courtyards 1 and 2 are sky gardens and situated on the tenth and sixth floors of the building; meanwhile, Courtyard 3 is a roof terrace and a component of the fourth roof terrace.

3. Multifunction Hall—Dongguan Taiwanese School, Dongguan (D1)

Two courtyards in the multifunctional hall have been connected. Courtyard 1 is a skylight courtyard, located on the third floor in the center of the building. Courtyard 2 is the sky garden, which is in the fringe area on the third floor on the south side of the building and is integrated with the vertical staircase.

4. Swimming Hall—Dongguan Taiwanese School, Dongguan (D2)

Courtyard 1, the skylight courtyard, is on the east side of the large pool, while Courtyard 2, the connecting courtyard, is on the south side of the first floor of the building and connects to the corridor space at the entrance of the building, creating a shaded semi-outdoor space.

5. Student Center—The Chinese University of Hong Kong, Shenzhen (S1)

Three courtyards were chosen for this study: Courtyard 1 is a roof terrace on the fourth floor of the building, surrounded by open area, and Courtyards 2 and 3 are connecting courtyards located in the same public space on the second floor of the building [26].

6. Student Dormitory—The Chinese University of Hong Kong, Shenzhen (S2)

The student residence is situated in the southwest corner of the campus. The design incorporates a variety of sky gardens into the bottom level courtyards, elevated platforms, and sitting platforms on the intermediate floors. The four chosen courtyards are divided among the ground and middle floors of the building. Courtyards 1, 2, and 4 are located on the ground floor. Courtyard 1 is an atrium located in the center of the dormitory building, while Courtyards 2 and 4 are an atrium and connecting courtyard, respectively. All three are arranged around the central courtyard. Courtyard 3, a sky garden, is located on the sixth floor of the dormitory and used daily by the students on that floor, where it combines with vertical traffic at the end of the plan.

2.2. Questionnaire Survey

A behavioral activity survey was conducted on the visitor population, and 322 valid questionnaire responses were gathered during the study period. The surveys were divided into two sections: basic personal data (e.g., gender and age) and activity data (e.g., frequency, duration, purpose, and main concern upon visiting) (Table 1).

Table 1. Questionnaire on visitor behavior.

Gender	1. Female 2. Male
Age	
Visit Frequency	1. rarely 2. Once per week 3. Twice per week 4. Three times and more per week
Visit Duration	1. <5 min 2. 5–20 min 3. 20–40 min 4. >40 min
Purpose of Visit	1. Relax 2. Meet friends 3. Pass by 4. Other
Main Concern of Visit	1. Availability 2. Accessibility 3. Weather Condition 4. Facilities 5. Greenery 6. Thermal Condition

2.3. Thermal Environment Test

Fixed measurements of thermal parameters were taken at the geometric centers of the 18 courtyards in clear weather from 09:00 to 17:00 in the summer of 2020. A fully exposed open environment near the courtyards was selected as a reference group to measure and record the corresponding thermal parameters, with data recorded every 10 min (Figure 2). Scarlet TWL-1S-Smart Stress Detectors were used to record the following parameters: air temperature (Ta/°C), black globe temperature (Tg/°C), wind speed (WS/(m/s)), relative humidity (RH/%), and sun radiation (SR(W/m^2)) (Table 2). To determine the mean radiation temperature ($Tmrt$), the following Equation (1) was used (ISO 7726, 1998):

$$Tmrt = \left[(Tg + 273)^4 + \frac{1.10 \times 10^8 Va^{0.6}}{\varepsilon D^4} (Tg - Ta) \right]^{\frac{1}{4}} - 273 \quad (1)$$

where *Tg* is the globe temperature (°C), *Va* is the wind speed (m/s), *Ta* is the air temperature (°C), *D* is the diameter of the globe (m), and ε is the emissivity.

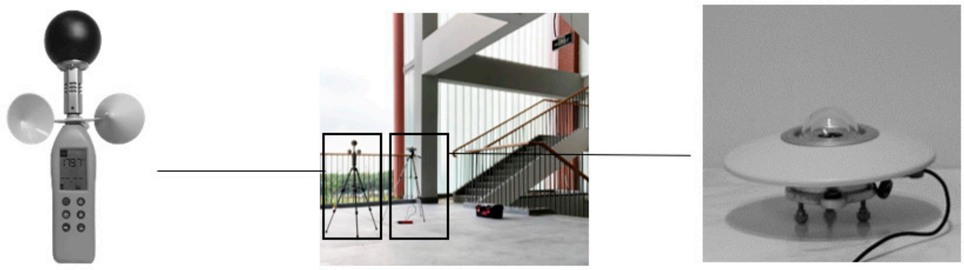


Figure 2. Facilities and measurement points. (**a**) Scarlet TWL-1S-Smart Stress Detectors; (**b**) Thermoelectric Solar Radiation Detectors.

Table 2. Thermal environment parameter measurement instruments and accuracy.

Thermal Environment Parameters	Measuring Instruments	Measurement Range	Instrument Accuracy
Air temperature	(a) Scarlet TWL-1S-Smart Heat Stress Detector	0–60 °C	±0.6 °C
Black globe temperature		0–80 °C	±1.5 °C (15–40 °C) ± 2.0 °C (others)
Relative humidity		5–95%	±3% (at 25 °C; 10–90% RH); ±5% (others)
Wind speed		0.5–10 m/s	±(2% of reading + 0.2) m/s
Solar radiation	(b) Thermoelectric Solar Radiation Detectors	0–2000 W/m^2	±3%

2.4. Courtyard Design Factor Test

The study used a diastimeter to measure the length, width, and height of the 18 courtyards examined, and recorded and calculated their size and aspect ratio. At the geometric center of the 18 courtyards, a fisheye camera was used to take photos, and RayMan was used to calculate SVF. After synthesizing the design factors involved in previous studies of the courtyards, and after conducting a site visit, new factors were selected for this study that were significantly different and could be quantified; i.e., the floor location, type, form, orientation, and landscape feature were measured and documented. The specific details on the architectural design factors of each courtyard are listed in Table 3.

Table 3. Information on architectural design factors.

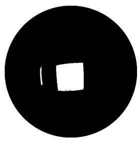
Factors/ Courtyard	Floor Location	Type	Form	Orientation	Landscape Feature	Size	H/L	SVF
H1–1	LG/F&UG/F	Connecting courtyard	Squarish	N and S	Hard pavement and planter	Extra-large (17 m × 24 m)	0.6	 0.043
H1–2	UG/F	Atrium	Squarish	N and W	Hard pavement and planter	Large (12 m × 14 m)	1.5	 0.069

Table 3. *Cont.*

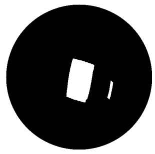
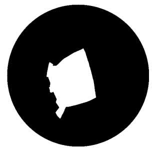
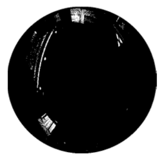
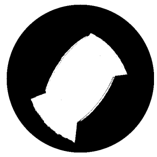
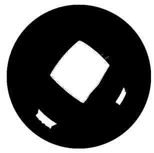
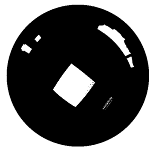
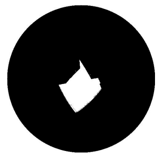
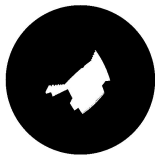
Factors/ Courtyard	Floor Location	Type	Form	Orientation	Landscape Feature	Size	H/L	SVF
H1–3	UG/F	Atrium	Squarish	W and E	Hard pavement	Large (12 m × 12 m)	1.4	 0.071
H1–4	2/F	Roof Terrace	Squarish	N and S	Hard pavement and planter	Large (12 m × 14 m)	0.7	 0.156
H2–1	10/F	Sky Garden	L-shaped	NE, N, and NW	Hard pavement and planter	Large (outer edge length: 25 m × 17 m)	1.3	 0.075
H2–2	6/F	Sky Garden	I-shaped	SW	Hard pavement and planter	Medium-sized (4 m × 13 m)	1.9	 0.067
H2–3	4/F	Roof Terrace	Roof	N, W, and S	Hard pavement and planter	Extra-large (23 m × 18 m)	5.9	 0.189
D1–1	3/F	Skylight courtyard	Squarish	n/a	Hard pavement	Extra-large (20 m × 36 m)	0.4	 0.065
D1–2	3/F	Sky Garden	Squarish	NE and SW	Hard pavement	Large (9 m × 12 m)	0.8	 0.081
D2–1	1/F	Skylight courtyard	Squarish	NW, SE, and SE	Hard pavement	Small (4 m × 4 m)	1	 0.027
D2–2	1/F	Connecting courtyard	I-shaped	SW, SE, and NE	Hard pavement and planter	Medium-sized (5 m × 10 m)	0.8	 0.243

Table 3. *Cont.*

Factors/ Courtyard	Floor Location	Type	Form	Orientation	Landscape Feature	Size	H/L	SVF
S1–1	4/F	Roof Terrace	Squarish	NW	Hard pavement	Extra-large (23 m × 15 m)	0.75	 0.344
S1–2	2/F	Connecting courtyard	Squarish	SE	Hard pavement	Large (13 m × 14 m)	1.25	 0.170
S1–3	2F	Connecting courtyard	Squarish	SW and NE	Hard pavement	Large (8 m × 16 m)	1.6	 0.106
S2–1	1/F	Atrium	Squarish	NW and SE	hard pavement	extra-large (19 m × 20 m)	1.8	 0.076
S2–2	1/F	Atrium	Squarish	n/a	Hard pavement	Extra-large (19 m × 28 m)	1.35	 0.115
S2–3	6/F	Sky Garden	Squarish	SE	Hard pavement	Small (6 m × 6 m)	1.1	 0.076
S2–4	1/F	Connecting courtyard	Squarish	SW, NW, and NE	Hard pavement	Large (9 m × 12 m)	1.3	 0.081

2.5. Calculation of Thermal Comfort Indicators

The PET is frequently used to measure the heat load that the human body places on the environment and to forecast the degree of heat stress that will be experienced by the body by taking into account both environmental factors and the physiological response of the human body. Numerous researchers have adopted a combined approach of field measurements and questionnaires to derive neutral physiological equivalent temperatures and investigate a range of generalized thermal climate indices in environments like tropical cities [27], temperate colleges and universities [28], and sunken plazas [29]. In this study, the RayMan 1.2 model was used to generate the model, and the PET was used as the thermal comfort rating index. The clothing condition was chosen to represent average summer clothing thermal resistance with 0.6 clo.

3. Results

3.1. Visitor Behavior Analysis

This study recorded the frequency, duration, purpose of visit, and environmental concerns of visitors (Figure 3). The frequency statistics (Figure 3a) showed that most visitors visited the courtyards three times per week on average (38%), followed by twice per week (32%), once per week (26%), and never (4%). The lower the floor on which the courtyards were located, and the more accessible they were, the higher the frequency of visits to them. In terms of duration (Figure 3b), the greatest proportion of visitors stayed for less than 5 min (57%), while 30% stayed for 5–20 min; those who stayed for more than 5 min typically visited courtyards that were adjacent to the building's function area (e.g., print room) or had additional seating options, factors which evidently lengthened their stay. Regarding the purpose of visit (Figure 3c), 59% of visitors simply passed by the courtyard, 26% engaged in relaxing activities, and 11% met up with friends. According to statistics on tourists' environmental concerns (Figure 3d), visitors were most concerned with the heat (22%), accessibility (21%), facilities (18%), and availability (17%), while in completely open courtyards, visitors were primarily worried about the weather.

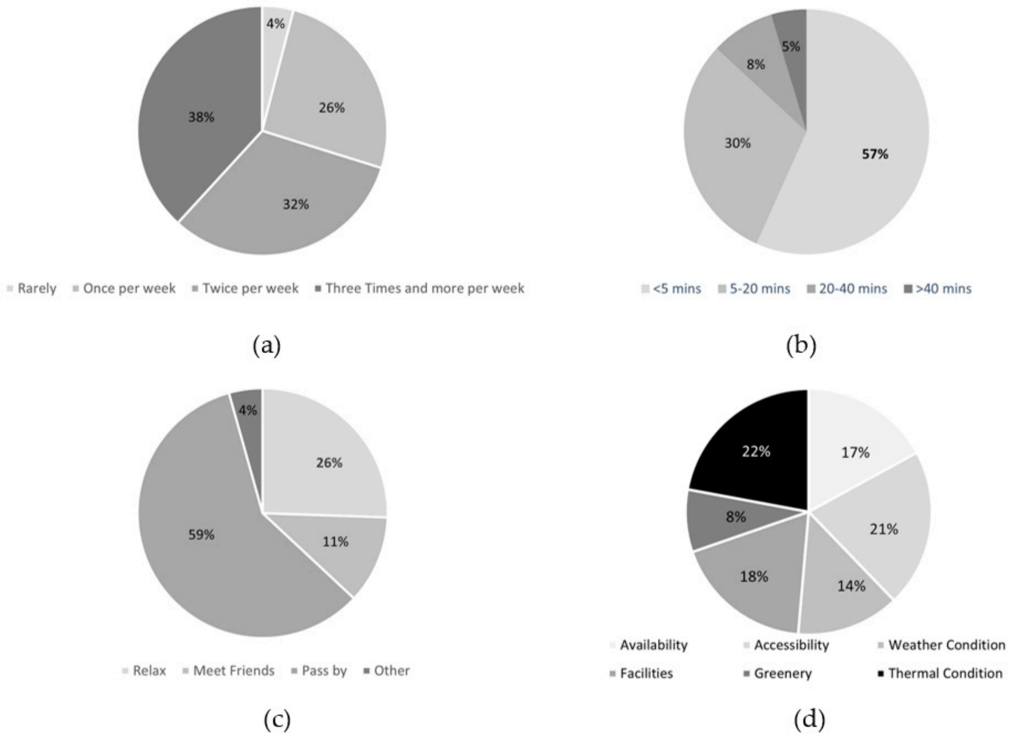


Figure 3. Visitor behavior analysis. (**a**) Visit frequency; (**b**) visit duration; (**c**) visit purpose; (**d**) main concern of visit.

3.2. Thermal Environment Parameter Statistics

Figure 4 presents the findings of this study, which evaluated the thermal environment parameters (air temperature, black globe temperature, mean radiant temperature, solar radiation, wind speed, and relative humidity) of 18 chosen courtyards. According to the results of air temperature measurements, 88% of the courtyards had mean air temperatures that were lower than the reference group, and the mean air temperatures of the courtyards ranged from 31.34 °C (S2–3) to 38.35 °C (S1–1), with minor variations between courtyards (Figure 4a). According to the results of the black globe temperature measurements, in 89% of surveyed courtyards, the mean black globe temperature was lower than that of the reference group, and the mean maximum black globe temperature reached 48.26 °C (S1–1), with a maximum temperature differential of 10.57 °C (S2–3) (Figure 4b). The mean radiant temperature measurements revealed that 83.3% of the courtyards had lower mean radiant temperatures than the reference group, with a maximum mean radiant temperature of 63.47 °C (S1–1) and a minimum mean radiant temperature of 30.14 °C (S2–3), and with relatively large differences between courtyards (Figure 4c). The solar radiation measurements revealed that the mean solar radiation in the surveyed courtyards was lower than that of the reference group, ranging from 6.91 W/m^2 (D2–1) to 738.68 W/m^2 (S1–1), with significant variations between courtyards (Figure 4d). Regarding the wind speed, 61.1% of the courtyards had lower mean wind speeds than the reference group, with mean wind speed intervals ranging from 0.02 m/s (D2–1) to 1.73 m/s (H2–2) (Figure 4e). Finally, the relative humidity measurements revealed that, on average, 66.7% of the courtyards had greater relative humidity levels than the reference group, with the range of mean relative humidity readings falling between 41.23% (D2–2) and 68.22% (H2–2) (Figure 4f).

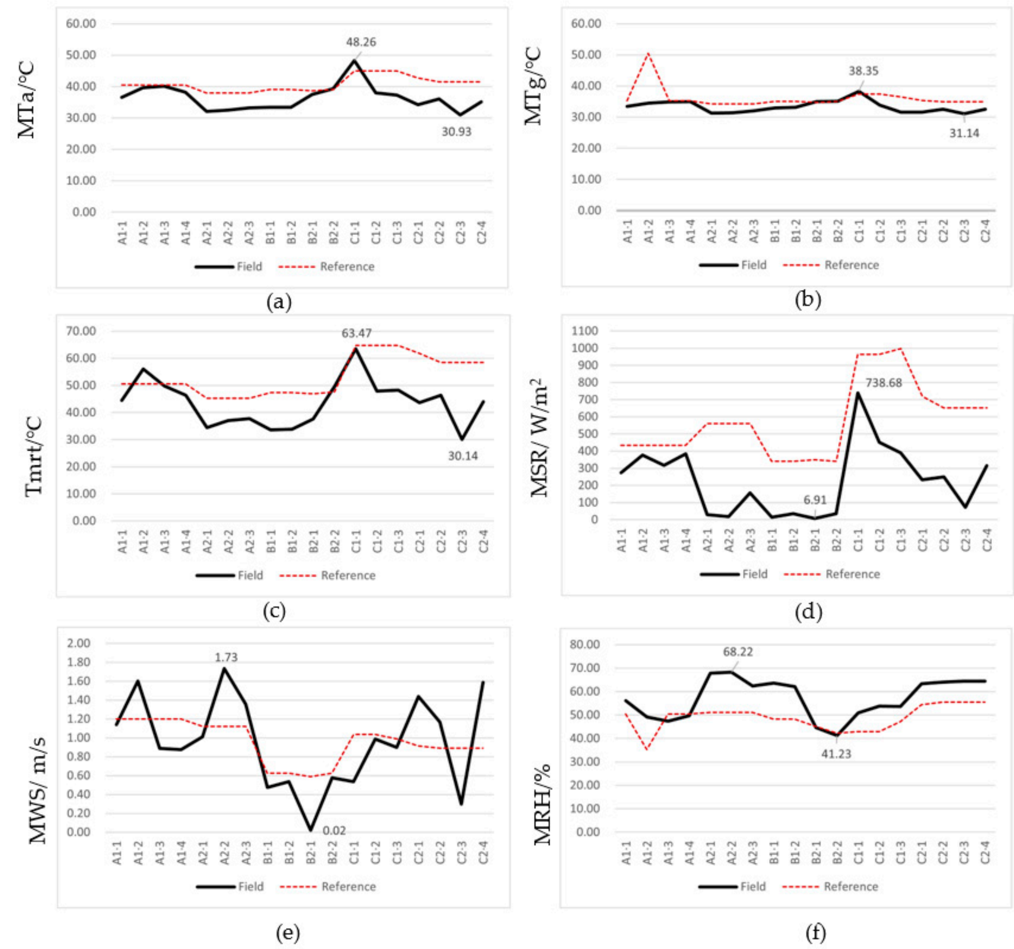


Figure 4. Statistics on physical parameters of the thermal environment. (**a**) Mean air temperature statistics; (**b**) mean black globe temperature statistics; (**c**) mean radiation temperature statistics; (**d**) mean solar radiation statistics; (**e**) mean air velocity statistics; (**f**) mean relative humidity statistics.

3.3. Correlation Analysis

3.3.1. Correlation Analysis between Thermal Environment Parameters and Design Factors

This study used statistical correlation coefficients to examine the relationships between the 18 campus courtyards' floor locations, types, forms, orientations, landscape features, sizes, aspect ratios, SVF, and thermal environmental parameters (Table 4).

Table 4. Correlation between thermal environment parameters and design factors.

Spearman Rho		**Ta**	**Tg**	**Tmrt**	**SR**	**WS**	**RH**
Correlation coefficient	Floor location	−0.472 *	−0.570 *	−0.487 *	−0.21	−0.17	0.543 *
	Type	−0.154	−0.462	−0.668 **	−0.653 **	−0.429	0.279
	Form	−0.238	−0.349	−0.166	0.43	0.294	0.204
	Orientation	−0.345	−0.525 *	−0.585 *	−0.471	−0.409	0.279
	Landscape feature	−0.011	0.055	−0.077	0.132	−0.407	0.033
	Size	0.02	0.042	0.159	0.301	0.262	0.139
	H/L	−0.509 *	−0.213	0.072	0.052	0.675 **	0.248
Pearson							
Correlation coefficient	SVF	0.509 *	0.645 *	0.585 *	0.546 *	−0.151	−0.333

Note: * Significant correlation at 0.05 level (two-tailed); ** significant correlation at 0.01 level (two-tailed).

The findings indicate a negative correlation ($p < 0.05$) between the mean air temperature, mean black globe temperature, mean radiant temperature, and floor locations of the courtyards; specifically, as the floor of the courtyard increased, all three variables decreased. The mean relative humidity of the courtyards showed a positive correlation ($p = 0.534$) with the floor locations, indicating a positive association between floor height and mean relative humidity. The mean air temperature of the courtyards was negatively correlated with the aspect ratio of the space ($p = -0.509$), implying that larger aspect ratios resulted in lower mean air temperatures. The mean black globe temperature and mean radiant temperature of the courtyards demonstrated negative correlations with courtyard orientation ($p < 0.05$); particularly, courtyards facing east exhibited lower mean radiant temperatures. Moreover, the mean radiant temperature and mean solar radiation were negatively correlated with the type of courtyard: sky garden and skylight courtyard types tended to have relatively lower mean radiant temperatures. However, no significant correlation was observed between the courtyards' form, landscape features, size, and thermal environmental parameters. In the summer in courtyards, the mean air temperature, mean black globe temperature, and mean solar radiation were positively correlated with the sky view factor (SVF). Higher SVF values in the courtyards led to increased solar radiation, higher mean air temperature, mean black globe temperature, and mean radiant temperature.

3.3.2. Correlation Analysis between PET and Design Factors

Spearman's correlation coefficient was employed to examine the relationship between PET and design parameters in 18 courtyards (Table 5). In summertime, PET was negatively correlated with the floor on which the courtyards were located ($p = -0.550$), with PET values decreasing as the floor of the courtyard increased. A correlation was also found with the type of courtyard ($p = -0.587$); specifically, the more open and less shaded the courtyard type was, the higher the PET value was. Additionally, a negative correlation ($p = -0.618$) was found between orientation and PET levels, with greater PET values observed for more west-oriented courtyards.

Table 5. Correlation between PET and design factors.

Spearman Rho		PET
Correlation coefficient	Floor location	−0.550 *
	Type	−0.587 *
	Form	−0.289
	Orientation	−0.618 *
	Landscape feature	−0.011
	Size	0.15
	H/L	−0.093
Pearson		
Correlation coefficient	SVF	0.651 *

Note: * Significant correlation at 0.05 level (two-tailed).

4. Discussion

4.1. Factors Affecting Visitors' Behavior

According to the questionnaire, visitors' attention to the courtyards was primarily centered on the thermal sensation and accessibility of the space. The presence of chairs or attractive landscaping were the most frequent characteristics that led visitors to the courtyards to stop or engage in other activities and behaviors. Skylight courtyards and sky gardens had the highest frequency of visits at three times per week on average, with 62.7% and 50%, respectively. Relevant studies have demonstrated that various factors affect visitor behavior. In addition to objective thermal environmental parameters, the evaluation of outdoor thermal comfort includes temporary psychological factors such as thermal expectations, visit purpose, and site functionality [30], which is supported by the empirical measurements presented in this study.

4.2. Differences in Thermal Environments of Courtyards

By examining the thermal environment parameters of the 18 examined yards, this study revealed that more than 80% of the courtyards had superior thermal environments compared with those in the reference group. Furthermore, the mean air temperature, mean black globe temperature, mean radiant temperature, and mean solar radiation in the measured courtyards demonstrated the same trend, and were inversely related to trends in mean wind speed and mean relative humidity. Among the thermal environment parameters, solar radiation exhibited the greatest difference between courtyards. Mean solar radiation showed the highest level of variation among all thermal environmental parameters in the courtyards examined. Comparing courtyards with the highest and lowest solar radiation levels, the D1–2 courtyard of the sky garden type experienced reduced solar radiation due to its smaller area, greater building height-to-width ratio, and the presence of partial shading provided by overhead structures. By being under the shadow of surrounding buildings for longer amounts of time, this courtyard experienced a lower thermal load.

4.3. Design Factors Affecting Thermal Comfort of Courtyards

The analyses revealed that courtyards on lower floors had better thermal performance in hot summer than those on higher floors. In hot summers, the mean radiant temperature has been found to be a significant factor influencing the body's energy balance and thermal comfort and has greater practical value than air temperature in determining human thermal comfort [31]. Analysis of the mean thermal radiation temperatures of the courtyards revealed that the mean radiant temperatures of the different types of courtyards were ranked as follows: skylight courtyard < sky garden < roof terrace < atrium < connecting courtyard. Most connecting courtyards had higher levels of solar radiation than the other types, while sky gardens and skylight courtyards had relatively low levels; this may be due to the fact that the latter mostly feature sheltered structures, which attenuate direct sunlight and thus improve thermal comfort. Liu Binyi et al. [32] already found that solar radiation is inversely proportional to the degree of overhead shading in summer in a thermal comfort study of a street in Shanghai. The mean radiant temperatures of the different courtyard orientations were ranked as follows: southeast orientation < full open orientation < southwest orientation < northeast orientation < northwest orientation < south-north orientation. This indicates that people visiting west-oriented courtyards experienced higher temperatures. This finding verifies the simulation conclusions of Qiao Zhengjun [19] that in the hot summer and warm winter regions, the design of the courtyards is recommended to prioritize the north, east, and south orientations. The aspect ratio is also related to thermal comfort; specifically, the higher the floor on which the courtyard is located, the better the air movement, which increases the ventilation effect and heat exchange effect of the courtyards and reduces the air temperature [33]. Zeng Zhihao et al. [34] also argued in the numerical simulation of thermal buoyancy in street canyons that the larger the aspect ratio of the canyon, the smaller the incoming wind speed, which can improve the replacement effect of the air inside the canyon. According to the study's correlation analysis, the floor location, type, orientation, and SVF are the primary factors impacting the thermal environment and PET of the courtyards. SVF is positively correlated with air temperature, black globe temperature, mean radiant temperature, and solar radiation, which means that the higher the sky openness coefficient, the higher the indicators of the aforementioned thermal environment parameters and the higher the PET. This result is consistent with the conclusion reached by Peng Xulu [35] in a microclimate study of street space that reducing SVF in summer reduces temperature and solar radiation. Additionally, the factors of floor location, type, and orientation were negatively correlated with the thermal environment and PET.

4.4. Strategies for Optimizing Thermal Comfort in Courtyards

Optimization of design strategies for the courtyards is essential because various types, orientations, and SVF may lead to different levels of thermal comfort.

- Strategy 1: Plan courtyards at relatively lower floors. In the study, it was found that when the type and orientation of courtyards are the same and the SVF is similar, the thermal environment of courtyards at lower floors is better than that of higher floors, e.g., S1–3 and S2–4, and the air temperature, the black globe temperature, and the average thermal radiation temperature of the S1–3 courtyard was higher than that of the S2–4 courtyard, so for the influence of different floors on the thermal comfort of courtyards, consideration can be given to increase the number of yards at lower floors when planning could provide a more comfortable thermal environment.
- Strategy 2: Add shading structures such as skylights at the top of the courtyard to reduce solar radiation. A comparison of different types of courtyards with the same floor location, orientation, and SVF revealed that the sky courtyard and skylight courtyard had better thermal comfort than other courtyards. Therefore, it is recommended to adopt certain top covering techniques, such as ceiling windows and other forms, which can ensure lighting and transparency, weaken direct sunlight, and improve thermal comfort (Figure 5).
- Strategy 3: Courtyard designs consider adding shading elements to diminish the effects of western exposure. Regarding courtyard orientation, west-oriented courtyards exhibited particularly poor thermal comfort. Under most circumstances, changing the orientation of the courtyards would not be practical; therefore, it is advised to reduce the negative effects of sunburn components by increasing the photovoltaic gradient in the western direction and thereby minimizing the impact of sunlight (Figure 6). Wang Yu et al. [36] proposed a sustainable retrofit idea from the perspective of integration with photovoltaic panels to reduce the impact of western sun exposure while realizing

the conversion and utilization of energy by means of laying an opaque over-water panel system on the western sun exposure surface. Zheng Shenhong et al. [37] realized more efficient shading by improving the push bar shading system by using the push bar drive motor combined with sensors to automatically adjust the push bar angle according to the sun's position and heat.

- Strategy 4: Select appropriate aspect ratios and landscape features to obtain appropriate sky visibility. When designing a courtyard, it is possible to choose an appropriate high-width ratio of the space, take advantage of the blocking effect, and reduce solar radiation to improve thermal comfort. Moreover, the surrounding environment can facilitate a certain amount of shadowing, for example, selecting native trees with a single umbrella canopy to optimize yard enhancement [38]. By establishing a microclimate, the courtyard can better regulate its own temperature and thereby improve the crowd's experience in the space (Figure 7). Based on the findings regarding visitor behavior, this study suggests that to maximize usage of the space, the courtyard design should focus on the accessibility of courtyards and provide an appropriate number of seats.

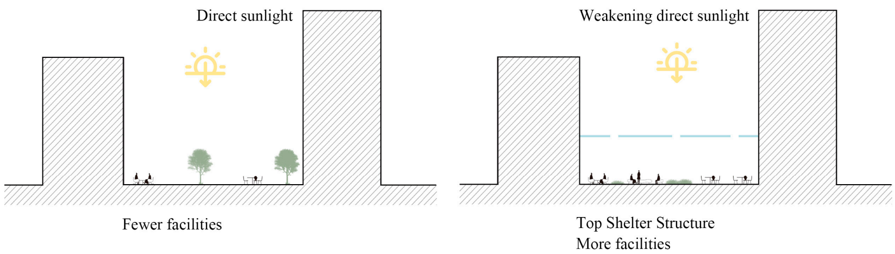


Figure 5. Adding skylight canopy to weaken solar radiation.

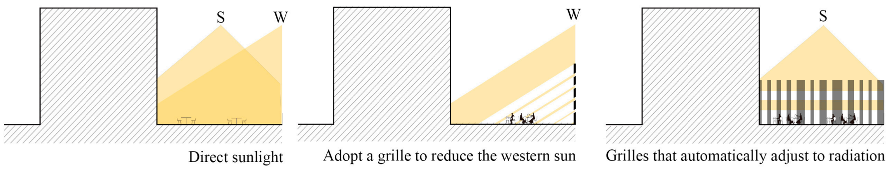


Figure 6. Adding shading elements to weaken the western sun.

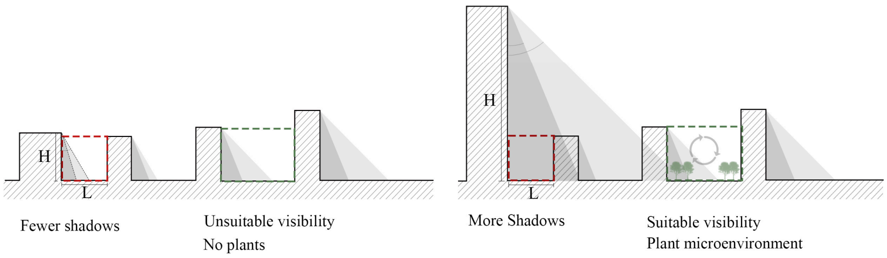


Figure 7. Appropriate increase in space aspect ratio and planting landscaper to obtain shade.

5. Conclusions

This study investigated the impact of architectural design factors on thermal comfort in courtyards in the Lingnan area during summer. The subsequent conclusions are as follows:

(1) The frequency of visits correlated negatively with the floor level on which each courtyard was located; specifically, the lower the floor, the higher the frequency of visits to the courtyards. Regarding the purpose of visits, more than half of visitors simply passed through the courtyards, and visitors' attention was primarily drawn to the feeling of heat and the availability of space.

(2) Most courtyards had a positive thermal effect: 80% of courtyards were lower than the reference group regarding mean air temperature, mean black globe temperature, and mean radiation temperature, while approximately 60% had higher mean relative humidity than the reference group.

(3) The floor location, type, orientation, and SVF of the courtyards were the main architectural design factors affecting their thermal environment and PET. The environmental thermal comfort evaluation index PET was negatively correlated with the floor location, type, and orientation of the courtyards, and positively correlated with the SVF, but not correlated with the form, landscape feature, size, and H/L of the courtyards.

(4) Based on the correlation between the thermal comfort of the courtyards and the architectural design factors, spatial modification can be carried out in terms of the four main factors: floor location, type, orientation and SVF. Planning the courtyards on a lower floor, adding shading structures such as skylights on the top of the courtyards to reduce solar radiation, adding shading elements to reduce the influence of western sunlight, and choosing appropriate spatial aspect ratios and landscape features to obtain appropriate sky visibility are all effective strategies to enhance the thermal comfort of courtyards.

6. Limitation

This study was conducted in summer. The following study shall focus on the remaining seasons, especially the transitional seasons, to further investigate the impact of design factors on the thermal comfort of courtyards.

Author Contributions: Conceptualization, Y.T., W.W. and X.L.; methodology, Y.T.; software, Y.L.; formal analysis, Y.L. and F.Z.; resources, W.W.; data curation, F.Z.; writing—original draft preparation, Y.T., Y.L., Z.C. and F.Z.; writing—review and editing, Y.T. and Y.L.; visualization, Y.L. and Z.C.; supervision, Y.T., W.W. and X.L.; funding acquisition, Y.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by National Natural Science Foundation of China (No: 52108018), Shenzhen Science and Technology Program (No: ZDSYS20210623101534001), Shenzhen Imported Overseas High-Level Talents Research Fund (No: RC00367, and No. FB11409007), Guangdong Province Education Planning Fund (Higher Education Special) (No. 2021GXJK064), and The Research Grants Council of Hong Kong General Research Fund Annual Progress Report (No. 17604117).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: All relevant datasets in this study are described in the manuscript.

Acknowledgments: The authors would like to offer thanks for the support from the Center for Human-oriented Environment and Sustainable Design, Shenzhen University. Thanks to Xu Zhu, Chen Liran, and Tian Mengxiao for their great help in the preliminary fieldwork and data collection.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

clo	Units of Thermal Resistance of Clothing	SR	Solar Radiation (W/m^2)
H/L	Height-to-Length Ratio	SVF	Sky View Factor
LG/F	Lower Ground/Floor	SW	South-Western
NE	North-Eastern	SE	South-Eastern
NW	North-Western	Ta	Air Temperature (°C)
n/a	Not Applicable (Unable to Define Orientation)	Tg	Black Globe Temperature (°C)
p	*p*-value	Tmrt	Mean Radiation Temperature (%)
PET	Physiologically Equivalent Temperature (°C)	UG	Upper Ground/Floor
RH	Relative Humidity (%)	WS	Wind Speed (m/s)

References

1. Wang, R.; Guo, W.; Dou, J.; Xie, H. Research on Green Building Wisdom of Lingnan Traditional Buildings Adapted to Hot and Humid Climate: Taking San-jian Liang-lang as an example. *Archit. Cult.* **2021**, *4*, 257–259. [CrossRef]
2. Chen, J.; Liang, Y.; Huang, G. Lingnan Architecture and Green Building: Based on Climate Adaption. *South Archit.* **2013**, *3*, 22–25.

3. Ghaffarianhoseini, A.; Berardi, U.; Ghaffarianhoseini, A. Thermal Performance Characteristics of Unshaded Courtyards in Hot and Humid Climates. *Build. Environ.* **2015**, *87*, 154–168. [CrossRef]
4. Taleghani, M.; Tenpierik, M.; van den Dobbelsteen, A.; Sailor, D.J. Heat Mitigation Strategies in Winter and Summer: Field Measurements in Temperate Climates. *Build. Environ.* **2014**, *81*, 309–319. [CrossRef]
5. Diz-Mellado, E.; López-Cabeza, V.P.; Rivera-Gómez, C.; Roa-Fernández, J.; Galán-Marín, C. Improving School Transition Spaces Microclimate to Make Them Liveable in Warm Climates. *Appl. Sci.* **2020**, *10*, 7648. [CrossRef]
6. Zamani, Z.; Heidari, S.; Azmoodeh, M.; Taleghani, M. Energy Performance and Summer Thermal Comfort of Traditional Courtyard Buildings in a Desert Climate. *Environ. Prog. Sustain. Energy* **2019**, *38*, e13256. [CrossRef]
7. Aldawoud, A. Thermal Performance of Courtyard Buildings. *Energy Build.* **2008**, *40*, 906–910. [CrossRef]
8. Diz-Mellado, E.; Patricia Lopez-Cabeza, V.; Rivera-Gomez, C.; Galan-Marin, C.; Rojas-Fernandez, J.; Nikolopoulou, M. Extending the Adaptive Thermal Comfort Models for Courtyards. *Build. Environ.* **2021**, *203*, 108094. [CrossRef]
9. Apolonio Callejas, I.J.; Durante, L.C.; Diz-Mellado, E.; Galan-Marin, C. Thermal Sensation in Courtyards: Potentialities as a Passive Strategy in Tropical Climates. *Sustainability* **2020**, *12*, 6135. [CrossRef]
10. Amirbeiki Tafti, F.; Rezaeian, M.; Emadian Razavi, S.Z. Sunken Courtyards as Educational Environments: Occupant's Perception and Environmental Satisfaction. *Tunn. Undergr. Space Technol.* **2018**, *78*, 124–134. [CrossRef]
11. Li, J.; Zheng, B.; Bedra, K.B. Evaluating the Improvements of Thermal Comfort by Different Natural Elements within Courtyards in Singapore. *Urban Clim.* **2022**, *45*, 101253. [CrossRef]
12. Apolonio Callejas, I.J.; Kruger, E. Microclimate and Thermal Perception in Courtyards Located in a Tropical Savannah Climate. *Int. J. Biometeorol.* **2022**, *66*, 1877–1890. [CrossRef]
13. Meng, Y.; He, J.; Zhao, X.; Qiu, J.; Huang, N. Measurements and Analysis of Summer Thermal Environments in the Atrium of Traditional Houses with Different Shapes of Atrium in tne Basin Region with Hot and Humid Cliamte. *Sci. Technol. Eng.* **2021**, *21*, 9035–9042.
14. Yang, L.; Liu, X.; Qian, F.; Niu, S. Research on the Wind Environment and Air Quality of Parallel Courtyards in a University Campus. *Sustain. Cities Soc.* **2020**, *56*, 102019. [CrossRef]
15. Jin, Y.; Jin, H.; Kang, J.; Hien, W.N. Field Study of Thermal Environment and Thermal Comfort in Public Spaces in Urban Resident Areas of Severe Cold Regions. *Build. Sci.* **2021**, *37*, 28–37. (In Chinese) [CrossRef]
16. Wu, Y.; Xu, G.; Li, M. Thermal Environment of Building Courtyard Space in Transitional Season in Severe Cold Areas: Taking the Courtyard Surrounding a Building of Inner Mongolia University of Technology as an Example. *Build. Energy Effic.* **2019**, *47*, 96–100.
17. Daramola, M.T.; Balogun, I.A. Analysis of the Urban Surface Thermal Condition Based on Sky-View Factor and Vegetation Cover. *Remote Sens. Appl. Soc. Environ.* **2019**, *15*, 100253. [CrossRef]
18. Yazdi, H.; Vukorep, I.; Banach, M.; Moazen, S.; Nadolny, A.; Starke, R.; Bazazzadeh, H. Central Courtyard Feature Extraction in Remote Sensing Aerial Images Using Deep Learning: A Case-Study of Iran. *Remote Sens.* **2021**, *13*, 4843. [CrossRef]
19. Qiao, Z. Effects of Courtyard Layout and Orientation on Office Building Energy Efficiency in Different Climate Zones. *J. Green Build.* **2020**, *12*, 20–24.
20. Liu, S.; Zhao, D.J.; Xu, M.; Ahmadian, E. Effects of Landscape Patterns on the Summer Microclimate and Human Comfort in Urban Squares in China. *Sustain. Cities Soc.* **2021**, *73*, 103099. [CrossRef]
21. Xie, M.; Li, J. Comparative Study on the Outdoor Thermal Comfort of Outdoor Plazas in Hot Humid Areas. *Urban. Archit.* **2020**, *17*, 52–55+67. [CrossRef]
22. Guo, X.; Bao, Z.; Wu, F.; Yang, S.; Yan, H. Influence of Street View Factors on Microclimate and Thermal Comfort of Urban Street Canyons in Summer Afternoon. *Chin. Landsc. Archit.* **2021**, *37*, 71–76. [CrossRef]
23. Li, M.; Jin, Y.; Guo, J. Dynamic Characteristics and Adaptive Design Methods of Enclosed Courtyard: A Case Study of a Single-Story Courtyard Dwelling in China. *Build. Environ.* **2022**, *223*, 109445. [CrossRef]
24. Wang, K.; Xue, S. Correlation Analysis of Building, Green Layout and Human Comfort in Summer in Urban Residential Areas: Taking Zhengzhou as an Example in Clod Region. *Build. Sci.* **2021**, *37*, 53–59, 71. [CrossRef]
25. Davtalab, J.; Deyhimi, S.P.; Dessi, V.; Hafezi, M.R.; Adib, M. The Impact of Green Space Structure on Physiological Equivalent Temperature Index in Open Space. *Urban Clim.* **2020**, *31*, 100574. [CrossRef]
26. Wang, W.; Yan, X.; Yu, X. The Chinese University of Hong Kong(Shenzhen) PhaseI. *J. Archit.* **2020**, *Z1*, 78–91. [CrossRef]
27. Sharmin, T.; Steemers, K.; Humphreys, M. Outdoor Thermal Comfort and Summer PET Range: A Field Study in Tropical City Dhaka. *Energy Build.* **2019**, *198*, 149–159. [CrossRef]
28. Yang, L.; Liu, J.; Ren, J.; Zhu, X.; An, F. Study on Outdoor Thermal Comfort of Campus Under Special High Temperture Climate in Transition Season. *J. Shandong Jianzhu Univ.* **2021**, *36*, 75–82, 96.
29. Hui, J.; Wang, Y.; Sun, L. Study on Thermal Environment of Tianjin Sunken Plaza in Winter. *Build. Sci.* **2022**, *38*, 101–107+224. [CrossRef]
30. Hu, X.; Li, B.; Chen, H. Research Review and Evaluation Framework of Outdoor Thermal Comfort. *Build. Sci.* **2020**, *36*, 53–61. [CrossRef]
31. Wang, Y.; Luan, P. Study on Thermal of Outdoor Public Space in Summer: Taking Contemporary Middle to Large Residential Area of Shanghai for Instance. *Hous. Sci.* **2016**, *36*, 52–57. [CrossRef]
32. Liu, B.; Peng, X. The Analysis and Evaluation of Thermal Comfort at Nanjing East Road, Shanghai. *Landsc. Archit.* **2019**, *26*, 83–88. [CrossRef]

33. Gao, Y. Measurement and Simulation of Outdoor Thermal Environment for Urban Residential District Planning. Ph.D. Thesis, Chongqing University, Chongqing, China, 2011.
34. Zeng, Z.; He, G. Study on the Impact Buoyancy on the Flow Field in Street Canyons with Different Aspect Ration. *Environ. Sci. Surv.* **2023**, *42*, 1–5. [CrossRef]
35. Peng, X. Study on Microclimate Adaptation of Street Space Based on Dynamic Thermal Comfort. *Build. Sci.* **2023**, *39*, 221–232. [CrossRef]
36. Wang, Y.; Chen, Y. Optimization of Exterior-protected Construction to Reduce the Influence of West Sunshine. *J. Heze Univ.* **2018**, *40*, 58–59. [CrossRef]
37. Zheng, S.; Yang, M.; Lin, X.; Zhang, P.; Zhan, S. Research on Building System Based on Push Type Photovoltaic Panel. *Eng. Technol. Res.* **2023**, *8*, 167–169. [CrossRef]
38. Wang, Q.; Qiu, Z.; Sun, H.; Zhong, B. Landscape Optimization Strategy of Living Street in Nanshan District of Shenzhen Based on ENVI-met Microclimate Simulation. *Community Des.* **2022**, *39*, 138–146.