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The Effect of Greening Layout on Microclimate in Urban Residential Areas in Hot Summer–Cold Winter Zones

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Abstract: Appropriate greening design can enhance the microclimate of residential areas. This study investigated different greening cases for residential buildings in hot summer–cold winter zones. Four sorts of greening layouts were tested in a residential area in Chongqing, China. Arbor–grass mix and arbor–shrub–grass mix showed effective cooling and humidifying effects, and were chosen for further study using the ENVI-met model. The simulations were conducted in Chongqing, comparing sixteen greening cases for determinant and enclosed building forms. Results indicate that the greening design for determinant layout should give priority to ensuring the greening area and shortening the distance from the sidewalk. While enclosed layout should concentrate greening in dense populations, using arbor–shrub–grass mix to improve the wind environment. In cases where the distribution of arbors and shrubs covers a ratio of 7:4, constituting 30% of the overall green space, there is a reduction in environmental temperature by 1.4 °C and in PET by 4.8 °C. This study provides the optimal greening layout for two types of residential areas in China's hot summer–cold winter zones, guiding landscape construction in these residential areas to optimize the microclimate.

Keywords: outdoor thermal environment; residential buildings; building layout; cooling effects of greening; urban microclimate

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1. Introduction

Rising urbanization and population growth have brought about numerous serious thermal environmental issues in urban residential areas. It is crucial to examine the current thermal environment problems in urban residential areas to guarantee residents' living quality and mental well-being [1,2]. To improve the outdoor thermal environment, domestic and international scholars have summarized key influential urban design factors and conducted studies on various types of cool pavements [3], exterior walls [4,5], the form of architecture [6,7], land height [8], greening [9,10], and water bodies [11]. Greening is one of the important factors that can easily improve and affect the outdoor thermal environment. The leaf transpiration and shielding effects of canopy leaves can effectively cool and humidify the surrounding air [12], even improving the urban microclimate, reducing building energy consumption, and mitigating the heat island effect [13,14]. Existing research has mainly focused on three types of greening layouts in the outdoor thermal environment, including roof greening [15], facade greening [16,17], and regional greening [18]. However, roof greening has been proven to be ineffective for human thermal comfort at 1.5 m above the ground [19], and facade greening has many restrictions and is challenging to maintain. For urban outdoor living spaces, regional greening becomes the prior solution for current environmental demand due to its rich functions and diverse forms.

Research findings confirm that the cooling and humidifying capacity of regional greening is related to several factors, including quantity [20,21], variety [22,23], and planting method [24]. A study by Huizhe Liu [18] of tropical residential areas in Singapore found that larger crown diameters or heights can effectively improve thermal comfort by creating a larger "urban green island". The larger the crown diameter, the greater the leaf area index (LAI), leading to a more noticeable improvement in the outdoor thermal environment [5]. In addition to LAI, thermal comfort from trees also depends on the leaf area density (LAD) at different heights. Tobi Eniolu Morakinyo [25] found that the trunk height of arbor has the weakest impact on human thermal sensation. In addition to the study of single greening species, Sodoudi and Zhang [26] found a correlation between the spatial patterns of greening and the cooling effect. Green vegetation arranged with less clustering or fragmentation is more effective in reducing surface temperature than a scattered arrangement [27]. Yujun Yang [28] examined the influences of three green spaces on thermal comfort in three residential areas with varying planting patterns. For the green space used for activities, the green space surrounded by trees will generate the most favorable thermal environment. For green space used for landscape, shrubs surrounded by trees provide optimal thermal comfort. Therefore, a comprehensive analysis of the impact of greening on the thermal comfort of residential areas should not only consider the greening types but also the combination of residential area layout.

Proper greening layout designs have a substantial impact on the thermal environment, affecting both wind speed and direction, and ultimately improving the quality of the outdoor environment [29]. The appropriate type of regional greening varies based on the diversity of climatic characteristics. For instance, in hot and dry climates, a simulation study by Zhao et al. [30] found that arranging two trees at equal intervals near residential areas provides the best thermal comfort, followed by cluster trees without overlapping crowns. In cold regions like Beijing, Bo Hong et al. [31] discovered that trees surrounding buildings, hinged by buildings, and facing the prevailing wind can create a comfortable wind environment for pedestrians. However, not all plants have a positive impact on the thermal environment [32]. Li et al. [33] studied high-rise residential areas in Singapore with a tropical rainforest climate and found that shrubs make people feel uncomfortable. It is confirmed that increasing urban vegetation coverage will reduce the Universal Thermal Climate Index (UTCI) of the tropical city of Singapore to below 3 °C at noon [33]. The increase in humidity not only reduces thermal comfort but also increases the energy consumption of dehumidification air conditioning [34]. Due to the combined influences on outdoor temperature, humidity, and wind speed, the urban greening design can be a multi-objective optimization problem with optimal planting layout differing across different climate zones.

Research methods to explore the impact of greening layout on the outdoor thermal environment include field tests, remote sensing [35], and numerical simulation. Early research relied primarily on field tests to evaluate the impact of various factors on urban microclimate [36,37]. However, due to limitations in terms of time, space, and cost, it is difficult to obtain universal rules through on-site testing. Remote sensing technology is mainly used to derive the surface temperature of the top canopy and identify extreme temperature areas, but it cannot directly analyze the thermal feeling of urban residents [30] and is rarely used in relevant research on greening. Numerical simulation methods have become increasingly prevalent in recent years. They overcome the limitations of remote sensing and can simulate outdoor microclimate and human thermal comfort. ENVI-met is well-used to evaluate the effects of green infrastructure on urban microclimates by providing microclimatic condition simulations and custom evaluation indicators, as highlighted by Zhixin Liu [38] in his review of urban green infrastructure systems. The research process with ENVI-met typically involves modeling, validation, and scenario simulation. Yupeng Wang [39] also confirmed the effectiveness of ENVI-met in exploring the cooling effect of vegetation. By using the ENVI-met microclimate fluid dynamic model to measure the impact of a greater green landscape area, the median air temperature could be reduced by about 0.5 °C [39]. Pingying Lin [40] used a combination of field tests and ENVI-met simulation to explore the outdoor greening design strategy in an old residential area in downtown Shanghai, and conducted a regression analysis to quantify the impact of different greening on thermal conditions. The conclusion is that the air temperature decreases by 0.05 °C, 0.28 °C, and

0.88 °C for every 10% increase in lawn, shrub, or arbor. Helge Simon [41] used ENVI-met simulation and empirical data comparison to study the interaction between vegetation and the urban thermal environment under four weather conditions. In existing research, there is a lack of the impact of greening layout on the outdoor thermal environment of different types of buildings, such as the impact of single greening and various mixed greening on the outdoor thermal environment of determinant and closed buildings. Especially in the hot summer and cold winter areas in China, there is a lack of case studies using ENVI-met tools to evaluate the best greening design.

Current research mainly focuses on the impact of ground green space coverage [30,42] and the number of arbors [5,20,21] on the outdoor thermal environment. Although greening is very effective in improving the outdoor thermal environment, there are still challenges in optimizing greening at a regional scale based on climate response. First, research on the effects of varying green combinations and layout at the same level of greening rate (the proportion of green space area in the land area) remains limited. Moreover, the building layout in residential areas can affect residents' habits and life quality, including microclimate, safety, and social interaction, thus also bringing challenges to greening solutions. Lastly, due to the impact of local climate on greening effectiveness, it is essential to incorporate regional climate factors into the entire process of greening case design and evaluation.

This study improves the study of the outdoor thermal environment in China's hot summer–cold winter climate zones. By observing the impact of single greening and various mixed greenings on the outdoor thermal environment in residential areas, the advantages of mixed greening were quantified. Compared to the cooling effect obtained by discussing the addition of single greening in existing studies, this study provides more spatial suggestions for greening layout design. Using a simplified physical model of experimental residential areas, the physical model is representative of common residential areas. Under the same greening rate, the impact indicators that combine greening layout and patch quantity were selected, and 16 greening cases with different arbor proportions, landscape fragmentation, and greening types were established. In addition, the effect of greening on outdoor thermal parameters was analyzed to provide the optimal greening design for the determinant and enclosed layout.

2. Methodology

2.1. Field Measurement Sites and Method

The experimental research was carried out at a community scale, focusing on a high-end residential area in Yubei District, Chongqing, that is rich in diverse greening types and layouts. The residential area covers 76,590 m^2, with a 35% greening rate, a plot ratio of 3.67%, and 1037 households. Considering the specific geographical environment of the whole experimental site, the test points of different greening types are arranged as shown in Figure 1 to minimize the effects of shading and wind speed caused by surrounding buildings. Four types of greening layouts, including arbor–grass mix, shrub–grass mix, single lawn, and arbor–shrub–grass mix, were selected, with a control group (asphalt ground). For the five measuring points, self-made vertical instrument racks were used, and the louver boxes were placed at a height of 0.1 m/0.5 m/1.0 m/1.5 m above the ground. The Apresys^{TM} temperature and humidity self-recording label were placed in a louver box, and the temperature and humidity at different heights were recorded every five minutes. The WFWZY-1 universal wind speed and temperature recorder and HQZY-1 black bulb thermometer were both arranged at a height of 1.5 m on the shelf, recording at five-minute intervals. The introduction and functions of the main instruments used in this study were listed in Table 1. After collecting microclimate data, the mean radiant temperature (T_{mrt}) for evaluating outdoor thermal sensitivity is calculated with Equation (1) based on ISO 7726 [43]:

$$T_{mrt} = \left\{ \left(T_g + 273\right)^4 + \left[\frac{1.1 \times 10^8 \times v_a^{0.6}}{\varepsilon_g \times D^{0.4}}\right] \times \left(T_g - T_a\right) \right\}^{\frac{1}{4}} - 273 \tag{1}$$

T_g—Black globe temperature (°C); T_a—Air temperature (°C); v_a—Wind speed (m/s); ε_g—Globe emissivity (0.95); D—Globe diameter (0.15 m).

Figure 1. Measuring points in Yubei, Chongqing (picture source: AMAP) [44,45].

Table 1. Instruments for field measurement.

Test Parameter	Instrument Model [46]		Range	Accuracy
Temperature/Relative humidity	ApresysTM temperature and humidity self-recording label		−20~60 °C 0% RH~99% RH	0.1 °C 0.1%
Wind speed	WFWZY-1 universal wind speed and temperature recorder		0~20 m/s	0.01 m/s
Black bulb temperature	HQZY-1 black bulb thermometer		−20 °C~+80 °C	0.1 °C

The experimental testing was conducted continuously from 21 July to 15 August 2018. According to the hourly meteorological data provided by the Xihe Energy Big Data Platform, the average air temperature during that period was estimated at 30.0 °C, with an average relative humidity of 71.5%. To analyze the microclimatic conditions of different greening layouts on a typical summer day, we selected the hourly average meteorological parameters on 22 July 2018 as the experimental days, as shown in Figure 2.

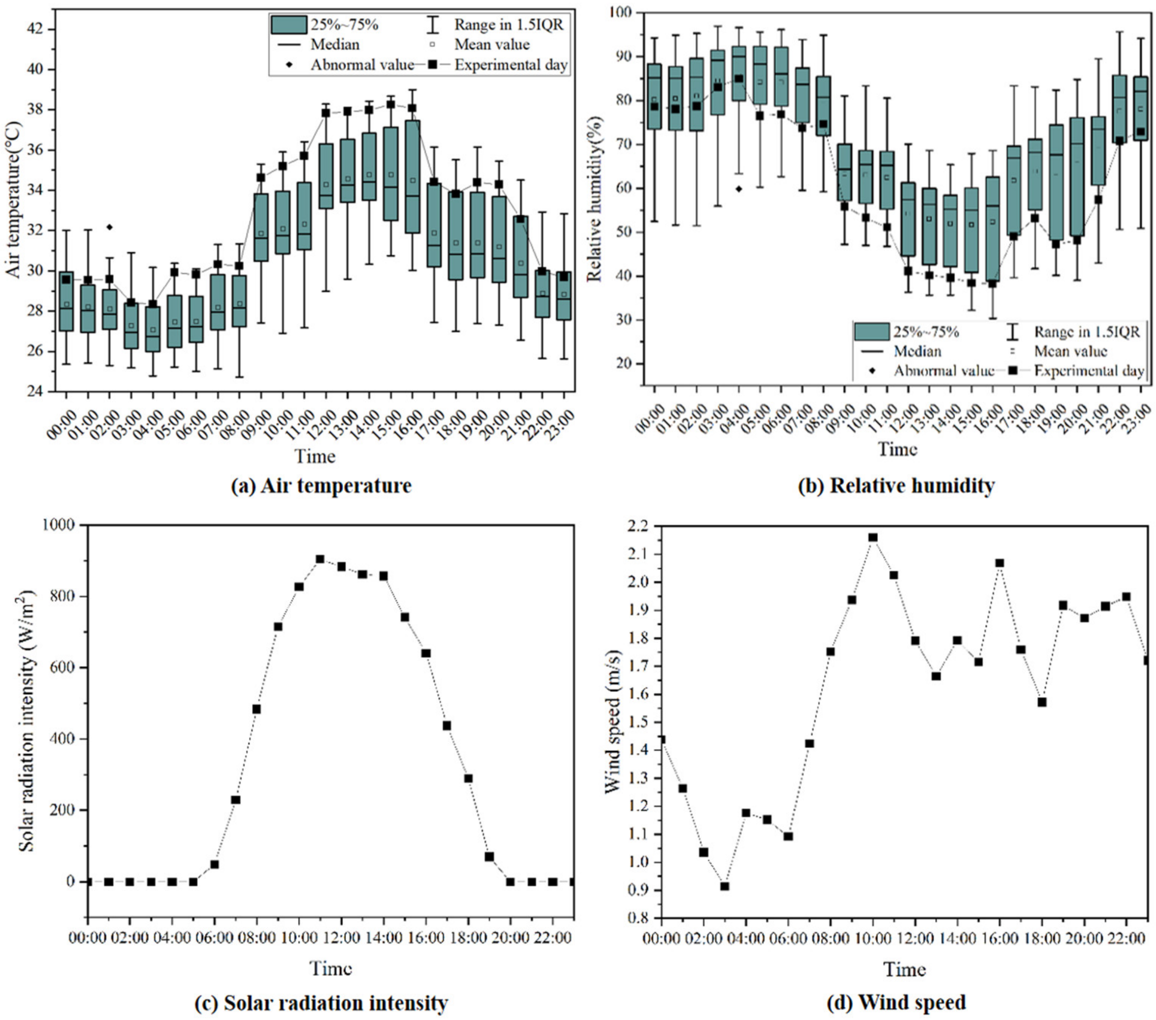


Figure 2. Meteorological parameters.

2.2. Model Setup

Accurate simulation of the outdoor thermal environment is crucial for quantifying the impact of different greening layout on outdoor thermal comfort enhancement. The paper conducts greening research at the community scale through outdoor thermal environment simulation models. Figure 3 shows the flowchart for simulation model development.

2.2.1. Model Framework and Parameter Setting

The scope of the simulation model was expanded beyond the experimental site to include adjacent villas, increasing simulation accuracy and incorporating a greater diversity of architectural forms. The model scope covers an area of 450 m in length and 260 m in width, consisting of two parts: one is an enclosed residential area surrounded by 11 high-rise buildings (building height: 102.4 m), and the other is a determinant residential area composed of villa buildings. There are 32 low-rise villas in a row layout with a height of 10.2 m. The simulation database was set up based on relevant literature [45,47,48] and field-measurement results.

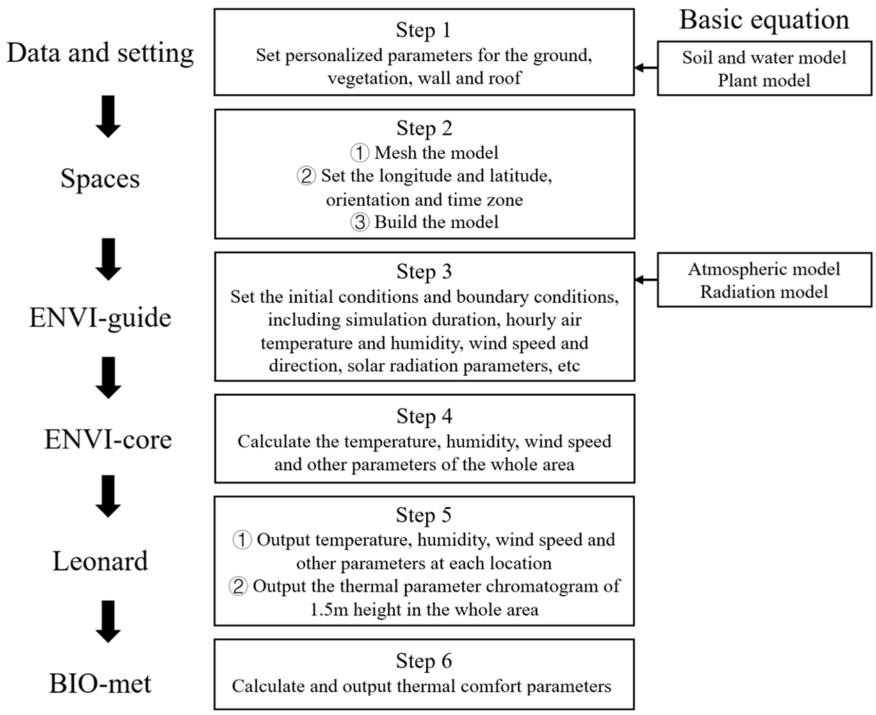


Figure 3. The flowchart of simulation model development.

1. Soil and ground;

The ground in the experiment plot consists of natural soil, concrete, and granite materials, along with a landscape fountain. To ensure maximum simulation accuracy, the initial parameters are set, as outlined in Table 2.

Table 2. Parameter settings of soil.

Material	Unit	Natural Soil
Water content at saturation	m^3 (Water)/m^3 (Soil)	0.45
Water content at field capacity	m^3 (Water)/m^3 (Soil)	0.24
Water content at wilting point	m^3 (Water)/m^3 (Soil)	0.155
Matrix potential	m	−0.478
Hydraulic conductivity	$m/s \cdot 10^{-6}$	7
Volumetric heat capacity	$J/(m^3 \cdot K) \cdot 10^6$	1.88
Clapp & Hornberger constant	/	5.39
Heat conductivity	$W/m \cdot K$	0.7838

The specific parameter settings are shown in Table 3.

Table 3. Initial parameter settings of ground.

Ground Type	Thickness (m)	Thermal Conductivity (W/m·K)	Roughness (mm)	Reflectivity	Emissivity
Natural soil	4.5	0.7838	1	0.17	0.94
Concrete	0.1	1.05	1	0.04	0.94
Granite	0.1	3.49	1	0.4	0.85
Wave	1	0.599	1	0	0.95

2. Vegetation;

Plants in ENVI-met are divided into simple plants and 3D plants, mainly defined by tree and crown geometry, leaf properties, and root geometry [38]. Considering the leaf area index of different plant types in Chongqing, as described in Ref. [47], the original vegetation data are amended to reflect actual conditions. Specific parameter settings are detailed in Table 4.

Table 4. Parameter settings of vegetation.

	Lawn	Shrub	Arbor
Transmissivity	0.35	0.2	0.1
Emissivity	0.25	0.15	0.15
Height (m)	0.5	1	7
LAD = 1/10	0.4	2.8	0.159
LAD = 2/10	0.4	2.8	0.23
LAD = 3/10	0.4	2.8	0.334
LAD = 4/10	0.4	2.8	0.482
LAD = 5/10	0.4	2.8	0.671
LAD = 6/10	0.4	2.8	0.848
LAD = 7/10	0.4	2.8	0.878
LAD = 8/10	0.4	2.8	0.827
LAD = 9/10	0.4	2.8	0.626
LAD = 10/10	0.4	2.8	0.075

3. Wall and roof;

Based on specific building parameters in residential areas of Chongqing and in combination with previous research by the research group [44], the setting parameters for walls and roofs are shown in Table 5.

Table 5. Parameter settings of roof and wall.

Type	Roof	Wall
Thickness (m)	0.3	0.3
Absorptivity	0.5	0.7
Transmittance	0	0
Reflectivity	0.5	0.5
Emissivity	0.9	0.9
Specific heat capacity (J/kg·K)	1300	1050
Thermal conductivity (W/m·K)	0.84	0.81
Density (kg/m^3)	1900	1800
Roughness (m)	0.02	0.02

2.2.2. Model Initialization

Based on the processing methods for boundary conditions in relevant literature and drawing on previous experience [39,49], we used simple forcing to set the boundary conditions in the software. The real-time meteorological data shown in Figure 2 were also applied to the boundary setting and validation of subsequent models. Based on previous research by the research group [44], the ENVI-met model of the residential area established has been proven to be a suitable tool for simulating the outdoor thermal environment of residential areas in Chongqing during the summer, and it is effective and reliable. Therefore, this study continued to use this ENVI-met model.

The study focused on two common types of building layouts in residential areas, namely, the determinant layout and the enclosed layout. To save simulation time, the physical model of the experimental site was simplified, and reference points were set up (Figure 4). This makes both determinant and enclosed residential areas more organized and representative. The parameter settings for the simplified model are shown in Table 6.

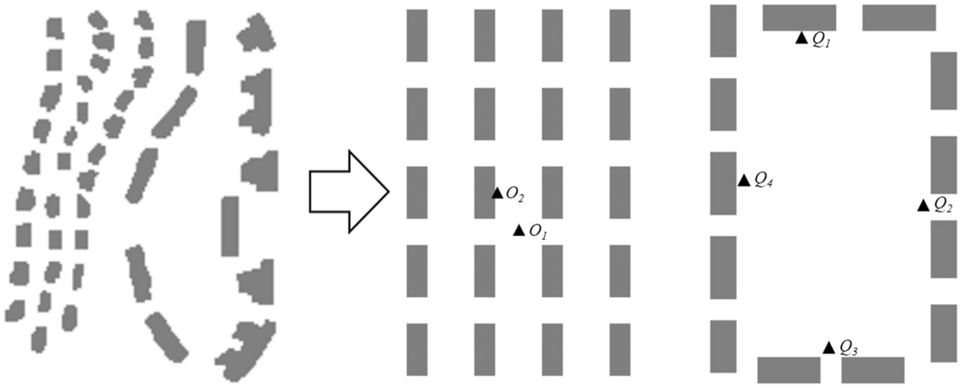


Figure 4. Schematic diagram of the simplified model and reference points.

Table 6. Initial settings of the ENVI-met model.

The Simplified ENVI-Met Model	
Location	29.72 N 106.63 E
Climate	Hot summer-cold winter
Grid cell	dx = 2 m, dy = 2 m, dz = 3 m
Grid north	22.5
Grid space for determinant layout	102 × 129 × 30
Grid space for enclosed layout	106 × 131 × 30
Distance between buildings	18 m
Buildings height	12 m
Reference points height	1.5 m

Due to limitations in the duration of experimental testing, the 2022 annual meteorological data of Chongqing was selected to calculate the typical summer days (data source: XIHE-ENERGY.COM). 29 July 2022 was selected as a typical summer day for simulated boundary conditions (Table 7).

Table 7. Weather conditions on the typical summer day.

City	**Air Temperature (°C)**		**Relative Humidity (%)**		**Wind Speed (m/s)**		**Solar Radiation Intensity (W/m²)**	
	Average	**Range**	**Average**	**Range**	**Average**	**Range**	**Average**	**Max. (Time)**
Chongqing	31.1	25.9–37.0	67.5	41.4–91.4	1.35	0.3–2.7	362.5	13:00

2.3. Simulation Scenarios

To quantitatively evaluate various greening cases, landscape fragmentation D_i is selected as the most suitable metric to describe the patch layout characteristics of plants, as it remains unaffected by the plant landscaping layout and can better represent the relationship between the number and area of landscape patches. Its calculation formula is as follows:

$$D_i = \frac{N}{S} \tag{2}$$

N—Number of landscape patches; *S*—Total landscape area.

In Figure 5, eight cases were simulated in determinant layout and enclosed layout, respectively, using different landscape patch fragmentation D_i and arbor proportion (the proportion of arbors in green space area). The simulation results were analyzed at the most uncomfortable time of 15:00.

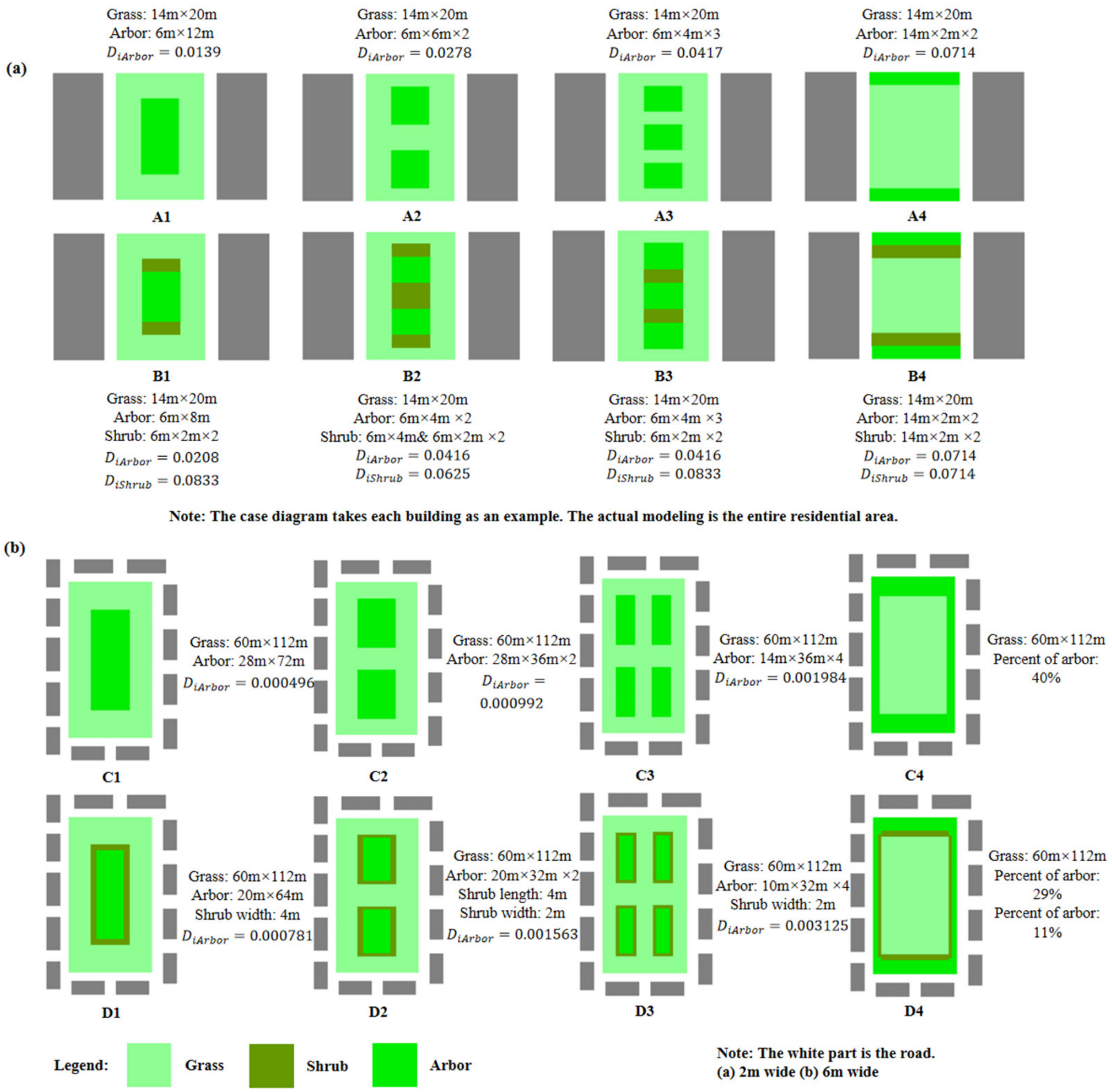


Figure 5. Summary of simulation cases.

3. Results and Discussion

3.1. Changes of Thermal Parameters for Various Greening Layouts

Figure 6 shows that at a pedestrian height of 1.5 m, the outdoor temperature and humidity changes in the four sorts of greening layouts are inversely proportional. The arbor–grass mix and arbor–shrub–grass mix demonstrate stronger cooling advantages, with the former maintaining lower temperatures throughout the day, particularly during 8:00–15:00. Additionally, the arbor–grass mix has the most pronounced humidifying effect, as evidenced by the highest relative humidity during this period. Overall, arbors have a significant impact on the cooling and humidification capacity, contributing to a stable outdoor environment with minimal temperature and humidity fluctuations.

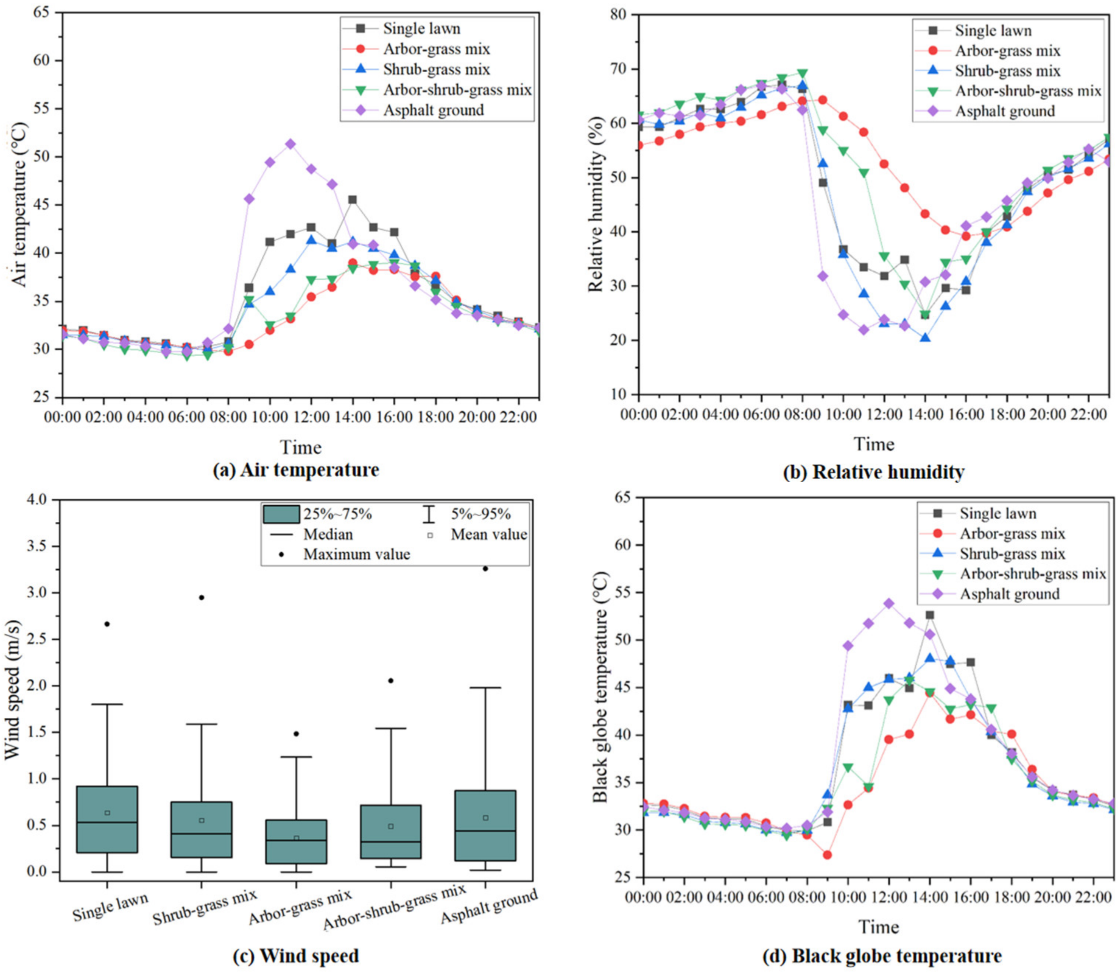


Figure 6. Hourly variations of measured parameters at 1.5 m height.

Environmental factors, such as distances from the main road and surrounding buildings, can inevitably influence the comparability of findings. The single lawn has the highest wind speed due to its proximity to the main road and lack of tall arbors around it. The shrub–grass mix had higher wind speeds than the arbor–shrub–grass mix at similar measuring points, indicating that greater complexity in greening can reduce wind speed. The arbor–grass mix had the lowest wind speed with the smallest fluctuation range, attributed to the presence of tall, dense foliage that provides strong shelter.

The most uncomfortable period in summer with high solar radiation occurs between 10:00 and 15:00. The moment of peak temperature under each greening layout differed and greatly related to the plant characteristics and surrounding buildings. Notably, at 9:00, affected by the sun's altitude angle causing significant shelter, there is a drop in black globe temperature under the arbor–shrub–grass mix greening layout. At 10:00, the solar altitude angle changed, and the black globe temperature increased obviously. Among all greening layouts, the outdoor black globe temperature fluctuation under the arbor–grass mix is relatively gentle and at a low level.

According to Table 8, the ranking of temperature and black globe temperature for the five greenings is: arbor–grass mix < arbor–shrub–grass mix < shrub–grass mix < single lawn < asphalt ground. The temperature difference between asphalt ground and arbor–grass mix is 3.0 °C, indicating a significant cooling effect due to greening on the outdoor environment. The changing trend of relative humidity is inversely proportional to the temperature. The ranking of wind speed is: arbor–grass mix < asphalt ground < arbor–shrub–grass mix < shrub–grass mix < single lawn.

Table 8. Mean values and variances of tested parameters under different greening layouts.

Greening Layout	Air Temperature Mean Value (°C)	Air Temperature Variance	Relative Humidity Mean Value (%)	Relative Humidity Variance	Wind Speed Mean Value (m/s)	Wind Speed Variance	Black Globe Temperature Mean Value (°C)	Black Globe Temperature Variance
Single lawn	35.6	23.66	49.3	181.31	0.62	0.16	36.9	45.67
Arbor-grass mix	33.4	8.65	53.0	68.32	0.41	0.10	34.8	20.55
Shrub-grass mix	34.7	15.48	47.7	234.21	0.58	0.22	36.4	40.86
Arbor-shrub-grass mix	33.5	10.74	52.6	167.60	0.49	0.16	35.3	28.14
Asphalt ground	36.5	47.68	47.9	234.29	0.45	0.17	37.8	64.79

To sum up, greening has the ability to optimize the outdoor thermal environment. Among them, arbor–grass mix and arbor–shrub–grass mix have better thermal comfort effects, but the specific effect is difficult to reflect through actual measurements, requiring further simulation research.

3.2. *Effect of Greening Design under Different Building Layouts*

The simulation results analyzed the improvement effect of 16 greening cases on the outdoor pedestrian height thermal environment at the most uncomfortable time of 15:00, and proposed suitable greening layout suggestions under the two most common types of building layouts (determinant layout and enclosed layout).

3.2.1. Determinant Layout

As shown in Figure 7, the fragmentation of arbor patches in cases A1, A2, and A3 increases while the green coverage and arbor proportion remain constant, leading to a decreasing trend in temperature. However, changing the characteristics of greenery does not significantly improve the thermal environment due to the small area of green patches. The temperature in the southwest of the residential area is relatively low. This is due to the combined effects of the position of the sun, building shading, and wind direction, resulting in a more comfortable thermal environment in the southwest of the residential area around 15:00. In contrast to the pattern of temperature changes, when the fragmentation of arbor patches increases from A1 to A3, the surrounding humidity shows an upward trend. In addition, when shrubs are added in B series cases, the humidity increases. A4 and B4 are more significantly humidified around buildings and crosswalks, while the center is still in a poor humidity condition. For wind speed, the wind speed of the B series case is higher than that of the corresponding A series case. This shows that the increase in shrub proportion has increased the wind speed. Moreover, although the layout of street trees reduces the temperature of sidewalks and lanes, it also makes the wind speed drop, as shown in A4 and B4 cases.

As shown in Figure 8, point O_2 on the pedestrian walkway is about 0.5 °C cooler than point O_1 on the roadway, indicating that greening has a weaker cooling and humidifying effect as distance increases. In the comparison of different green cases, case B4, with arbors on both sides of the street and increased shrub proportion, achieved the lowest temperature. However, this design may hinder the recreational functionality of the lawn space due to the impact on entrances and exits.

Therefore, for residential areas in a determinant layout, there is a significant limitation on the area of greening. The greening layout of street trees, such as case B4, was selected with a small advantage. This is consistent with the research result in Ref. [28] on residential areas, which states that shrubs surrounded by arbors can achieve the best thermal comfort layout in residential areas, preferably with active boundaries. However, its cooling advantage is relatively weak, consistent with Ref. [50], which also mentions the shading effect of high-rise buildings. The shading effect of a row layout building has a greater impact on the outdoor thermal environment than greening. Meanwhile, the row layout itself has a better cooling effect than other layouts [51], avoiding the impact of obstructing airflow caused by the complexity of greening. The greening layout design of a row-style residential area should comprehensively consider the solar angle and building height.

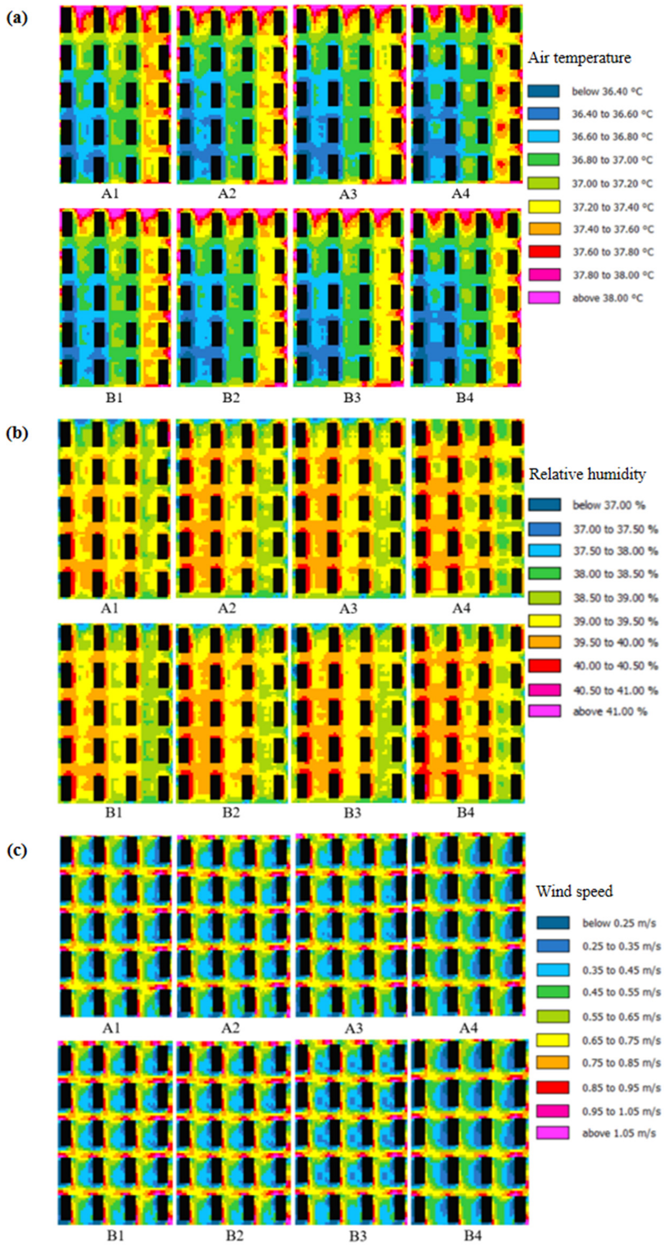
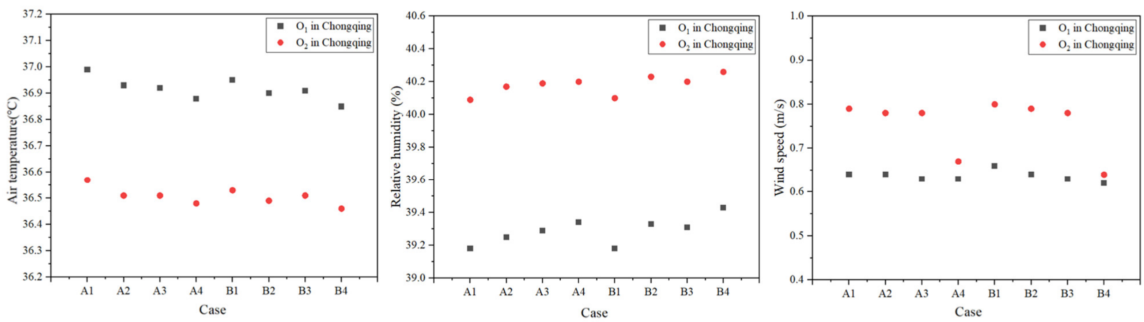


Figure 7. Chromatogram of different greening cases under determinant layout at 15:00; (**a**) air temperature, (**b**) relative humidity, and (**c**) wind speed. (The numbering information of A1–B4 is the same as that in Figure 5).



(a) Air temperature (b) Relative humidity (c) Wind speed

Figure 8. Reference points at 1.5 m under determinant layout.

3.2.2. Enclosed Layout

In the enclosed layout, the green area is large and concentrated, resulting in a relatively significant improvement in the thermal environment (Figure 9). From C1, C2 to C3, as the fragmentation of arbor patches increases, the proportion of areas with temperatures below 37 °C gradually decreases, and the central temperature first rises and then falls. Correspondingly, the surrounding humidity decreases, especially in the central point of the enclosed residential zone, and the proportion of areas with relative humidity over 39% gradually decreases. This indicates a weakening of the cooling and humidifying ability of arbors in the surrounding environment, and the cooling and humidifying effect of arbors decreases with distance. Comparing the C and D series cases, with the arbor ratio decreasing and the shrub ratio increasing, no significant temperature changes were observed. However, increasing the number of shrubs led to a higher diversity of green plants and a significant increase in humidity.

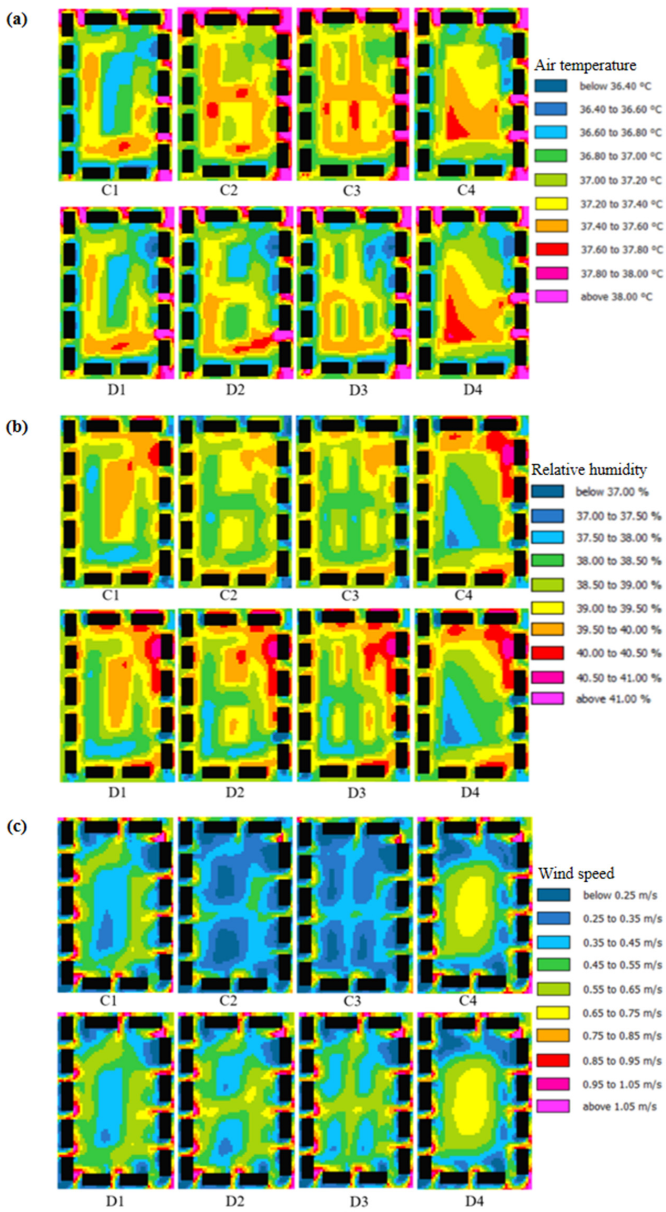
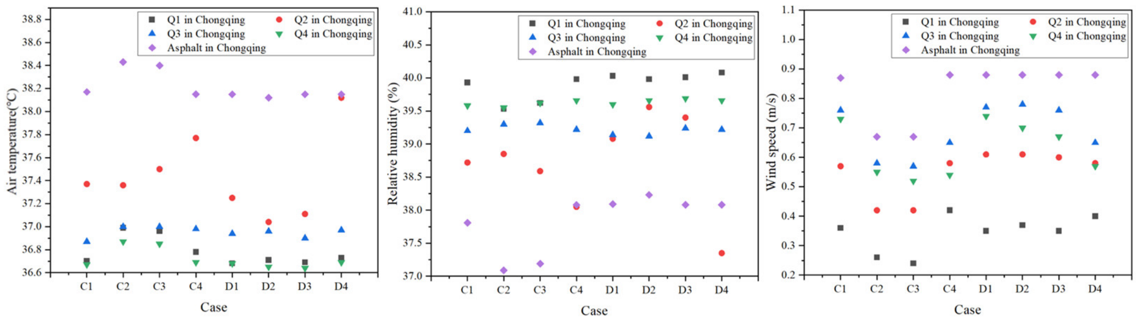


Figure 9. Chromatogram of different greening cases under enclosed layout at 15:00; (**a**) air temperature, (**b**) relative humidity, and (**c**) wind speed. (The numbering information of C1-D4 is the same as that in Figure 5).

For the wind environment, in C1, C2, and C3 cases, the area where the wind speed decreases is related to the location of the arbor patch, that is, the arbor patch will weaken the outdoor wind speed of the residential area. After replacing some arbors with shrub patches, the wind speed under condition D increased slightly. In C4 and D4, the street tree type layout is not suitable for enclosed layout.

As shown in Figure 10, closed residential areas in hot summer–cold winter climates should choose the D1 case to achieve the best level of cooling and humidifying. The best cooling effect in the D1 case was 1.4 °C, while in the C4 case, it was only 0.8 °C. The wind speed is more affected by orientation compared to greening layout. It is worth mentioning that under the condition of a high degree of arbor fragmentation, the arbor patch is closer to the sidewalk, which has a more significant impact on the wind speed of the sidewalk.



(a) Air temperature (b) Relative humidity (c) Wind speed

Figure 10. Reference points at 1.5 m under enclosed layout.

As shown in Table 9, the fragmentation of arbor patches gradually increased, and both T_{mrt} and PET increase rapidly and then decrease slightly. This is enough to indicate that the smaller the degree of fragmentation of tree patches, the better their comfort effect. The slight decrease in cases 2 and 3, combined with Figure 9, is due to the better circulation of wind in case 3. This shows that the fragmentation degree of arbor patches and the distance between arbor patches are the factors that affect the PET value at a certain point in the residential area. In the D series case, with the addition of shrub patches, T_{mrt} and PET are reduced, and comfort is improved. In general, according to the PET evaluation indicator and Figure 9, the diversity of greening types, low fragmentation of arbor patches, and the small spacing between arbors and sidewalks are most conducive to improving the outdoor thermal environment of enclosed residential areas.

Table 9. Mean Radiant Temperature (T_{mrt}) and Physiological Equivalent Temperature (PET) of different greening cases under enclosed layout.

Case	**T_{mrt}**		**PET**	
	Center	**Asphalt**	**Center**	**Asphalt**
C1	51.1	62.5	44.5	49.2
C2	64.4	65.4	52.7	49.2
C3	64.1	65.5	52.3	49.2
C4	61.0	62.2	48.6	49.2
D1	51.0	62.6	44.4	49.2
D2	61.4	62.6	49.4	49.2
D3	61.3	62.6	49.2	49.2
D4	61.0	62.3	48.6	49.2

Overall, for residential areas in an enclosed layout, the most suitable greening layout is to centrally arrange greening in densely populated areas with arbor–shrub–grass mix. Its optimality is consistent with the fact pointed out in Ref. [28] that green spaces are concentrated in the center of residential areas. Compared with the temperature of asphalt, the overall cooling and humidifying effect of the D1 case is the most significant, with a decrease of 1.4 °C in the center air temperature, 11.6 °C in T_{mrt}, and 4.8 °C in PET. This represents a decrease of 0.6 °C compared to the worst case C4. Compared to studies using ENVI-met for simulation, such as the 0.88 °C temperature reduction caused by adding 10% arbors [40] and the median temperature reduction caused by directly expanding the landscape area by 0.5 °C [39], this study found that the cooling effect of greening design was significant without changing the greening rate.

4. Conclusions

Based on summer measurements of outdoor thermal environments in a residential area in Chongqing, the cooling and humidifying capacity of four different greening layouts were compared. Results showed that the arbor–grass mix layout had the greatest cooling and humidifying capacity, followed by the arbor–shrub–grass mix, shrub–grass mix, and single lawn. The proportion of arbors in the greening layout had the most significant impact on cooling and humidifying capacity, while greening weakened wind speed, and the proportion of arbor area had a greater impact on wind speed at a height of 1.5 m above ground.

After verifying the developed ENVI-met model's feasibility in studying outdoor thermal environments in Chongqing's residential areas, the initial model was simplified to include two types of residential areas: determinant and enclosed. Considering the influencing factors of greening species, arbor proportion, and landscape fragmentation in the experimental test, the outdoor thermal environment improvement effects in Chongqing, representative cities of hot summer–cold winter, were analyzed. The major conclusions are as follows:

Firstly, regardless of the building layout, the case study indicates that the closer the greenery is to the point, the more pronounced the cooling and humidifying effects become. Furthermore, the thermal environment at the selected point is affected by the presence or absence of building shelters, the wind direction on the given day, and the altitude angle of the sun.

Secondly, in the determinant layout, increasing greening diversity and reducing the distance between green areas and sidewalks are effective for improving cooling and humidification. Arbors have a greater impact on pedestrian-level wind speeds compared to shrubs. Therefore, prioritizing green areas near sidewalks is crucial in determinant layout greening design. However, limited green space and increased fragmentation may not be cost-effective for temperature reduction and may negatively affect the wind environment. Street tree layout that maximizes shaded areas on sidewalks and incorporates shrubs are the most suitable greening design approach.

Thirdly, in the enclosed layout, increasing the fragmentation of greening patches raises temperatures and reduces cooling capacity. The wind speed within residential areas rises, but overall wind speed decreases. Changing the proportion of arbors and shrubs affects local temperature variation but has little impact on overall temperature change while improving the wind environment. When the area of trees and shrubs is concentrated at 7:4, occupying a total of 30% of the green space, the environmental temperature decreases by 1.4 °C, Tmrt decreases by 11.6 °C, and PET decreases by 4.8 °C. Centralized arrangement of greening is recommended for better cooling effects. When selecting arbor patch locations, consider areas with higher people density.

5. Limitations and Future Work

The study focused on three main influencing factors: proportion of arbors, landscape fragmentation, and greening types, evaluating indicators such as temperature, humidity, wind speed, and shading effect. In this paper, air temperature is the main metric used in the comparison of the thermal environment. Now, the globe temperature value is the average value of the air temperature and the mean radiant temperature. This means that the surface temperature is close to the air temperature. This is due to the systematic inertia exhibited by 150 mm globes, which cannot effectively measure the average radiation temperature outside [52,53]. In addition, the globe receives heat from solar direct and diffuse radiation, so higher values are expected. At higher temperatures, there will be more different thermal environmental effects, which will be taken into account in future work.

While considering common research methods and parameters of the outdoor thermal environment, this study has several limitations, such as not combining the objective comfort of the green layout with subjective personnel evaluation. The study also lacked quantitative calculation on the economy of greening layout, and no economic considerations were given for the actual greening design of the project. The actual residential terrain was not taken into account, and an idealized equal distribution layout was adopted. Future work can include subjective experiments through questionnaires to obtain feedback under different green layouts and quantitatively calculate their economic efficiency. The study can also consider changes in thermal environment parameters under different climate types, plant heights, house orientations, and height differences to carry out comparative studies and draw more detailed and accurate conclusions.

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