ENVI-met Simulation of Green Plant Layouts for Urban Thermal Comfort Optimization

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Different green plant layouts exert crucial impacts on human thermal comfort. The existing green plant layouts in urban streets have not achieved more ideal results in regulating temperature, humidity, and solar radiation. Therefore, in order to design a more livable urban environment, this study analyzes the green plant layout pattern of Street A in a certain city and explores its impact on regional thermal comfort. The study first designs different green plant layouts. Then, the meteorological factors that contribute to the thermal comfort of the region based on an urban microclimate treatment model are analyzed. The ENVI-met is used to simulate the changes of three meteorological factors, temperature, humidity, and wind speed, under four different green plant layout schemes. The average temperatures of the four simulation schemes were 26.58 ℃, 26.94 ℃, 25.03 ℃, and 27.31 ℃, respectively, verifying the regulating effect of green plants on air temperature. The average daily predicted voting values for the four different simulation schemes were 0.55, 0.71, 0.46, and 0.21, respectively, indicating that shrubs and trees had a significant regulatory effect on human thermal comfort. The RMSE and WMAPE error values of different schemes were all below 4%, which was within a reasonable range, indicating that this modular scheme had high accuracy performance. This indicates that the design scheme can effectively simulate local microclimate changes, providing effective data support for regional climate regulation, improving local thermal comfort, and providing a more comfortable and livable working and living environment.

Povzetek: Raziskava uporablja model ENVI-met za simulacijo vpliva različnih razporeditev zelenja na mikroklimatske dejavnike in izboljšanje toplotnega udobja, kar omogoča načrtovanje bolj prijaznih urbanih okolij s pomočjo izbrane konfiguracije zelenja.

1 Introduction

Urbanization has brought about more superior and convenient living conditions. With the gradual improvement of living conditions, people have put forward higher requirements for the natural environment of their living areas. Higher quality urban livable environment optimization is urgent. Greening is one of the key factors affecting the regional climate in urban development. Urban green space includes road greening, park greening, ecological green space, and other ancillary green land. While meeting daily rest and sightseeing needs, it can effectively regulate and improve the urban microclimate [1-2]. The green plants in urban street areas play a key role in absorbing carbon dioxide, purifying the air, blocking solar radiation, and improving environmental temperature. The green space system generally includes arbors, shrubs, and grasslands. Different green plant layout patterns have different impacts on the local microclimate, which is directly reflected in the perceived thermal comfort level by the human body [3-4]. The thermal comfort of an area is generally determined by multiple physical factors such as temperature, wind speed, and rain. The green space layout pattern has a direct impact on these physical factors. Reasonable plant arrangement and layout can produce more significant climate regulation effects, thereby affecting thermal comfort [5]. Therefore, adopting more scientific and reasonable methods to layout green plants on urban streets is of crucial significance in regulating local environmental climate and increasing thermal comfort.

Many scholars have analyzed the impact of vegetation arrangement on meteorological factors such as temperature and humidity. Andrew S C et al. simulated the expected climatic limits of trait combinations using trait data on leaf size, seed quality, and plant height from 27 plant families. The results indicated that the combination of functional traits was a meaningful predictor of species climate and ecological indicators, which had potential relationships with rainfall and temperature variables [6]. Madhavan G et al. used binomial logistic regression to evaluate the impact of open and low growing plants on urban microclimate. Due to the influence of surface temperature, the regional differences between various climate variables were higher than the inter regional differences. Providing information on suitable forms of warm and humid climates can help formulate regulatory policies [7]. Zhao K et al. used a trend seasonal component model to analyze the impact of vegetation phenology on climate change, which decomposed vegetation phenology into time series. The results showed that winter precipitation was the primary factor indirectly affecting the advance or delay of the growing season. The indirect effects of autumn temperature and precipitation were the main factors affecting the delay and advance of the end of the growing season, respectively [8]. Gao J et al. monitored the effects of various vegetation type combinations on riverbank ecological engineering construction and evaluated the improvement effect of various vegetation type combinations on microclimate. The combination of vegetation types could effectively regulate microclimate and human comfort [9]. Chen X et al. simulated the impact of farmland and vegetation types on primary productivity in the Yangtze River Delta from 2001 to 2020 using an ecosystem productivity simulator. The results showed that in some key green areas, leaf area index dominated the changes in primary productivity [10].

The Environment for Visualizing Images (ENVI-met) urban microclimate processing software can be used for simulating and analyzing microclimate elements. For example, Kamata Y et al. used ENVI-met to analyze the improvement effect of continuously vacant residential and open space greening on outdoor thermal environment in the densely built old city area of Busan. The thermal environment of the concrete scenario was the worst, with an increase of 0.04℃, 1.49℃, and 0.51℃ in average temperature, average radiation temperature, and physiological equivalent temperature, respectively [11]. Qin Z et al. used ENVI-met software to analyze the microclimate of Dayuwan Village Square in Wuhan City. It quantitatively evaluated the impact of 15 scenarios, including building greening, tree planting, albedo regulation, and expanding tree coverage, on outdoor temperature. This study provided sustainable guidance for designers to enhance mitigation effects by optimizing landscape configuration, demonstrating a technical framework for improving rural environments [12]. Ma X et al. used ENVI-met to predict the relationship between courtyard and outdoor thermal environment in traditional residential settlements in cold climate regions of northern China. The conclusion indicated a close correspondence between simulated and measured data [13]. Elnabawi M H et al. explored parameterized energy modeling of energy-saving loads and indoor air temperature, as well as microclimate modeling of outdoor air temperature. Simulation predictions showed that the cold load on cold roofs and green roofs was reduced by 10% and 7.5% compared with traditional roofs, respectively [14]. The existing research mentioned above is shown in Table 1.

Table 1: Advantages and disadvantages of existing solutions

Literature	Content	Achievements	Disadvantage
[6]	The impact of plant trait combinations on local climate	The combination of functional traits is a significant predictor of climate indicators	The specific relationship between plant traits and local climate change has not been explained
[7]	Evaluating the impact of open and low growing plants on urban microclimate	It helps to formulate temperature regulation policies	Unclear impact of climate variables on temperature
[8]	Using seasonal component models to analyze the impact of vegetation phenology on climate change	The indirect impact of precipitation on the growth of green plants	/
[9]	Exploring the improvement effect of different vegetation type combinations on microclimate	Vegetation combination can effectively regulate microclimate and human comfort	The impact of specific vegetation combination schemes on human comfort is unclear
[10]	Simulating the impact of green areas on primary productivity.	The key green areas dominate the changes in primary productivity	Not considering whether productivity has an impact on green area and green scheme
[11]	Using ENVI-met to analyze the improvement effect of open space greening on outdoor thermal environment	The thermal environment in the concrete scenario is the worst	No detailed comparison has been made on the green space
[12]	Evaluating the impact of tree planting, building greening, albedo regulation, and expanding tree coverage on outdoor	Providing guidance on mitigating outdoor temperatures by optimizing landscape configuration	Not considering other factors that may affect thermal comfort, such as humidity, ground conditions, etc

	temperature		
[13]	Predicting the Relationship between Residential Courtyard and Outdoor Thermal Environment	There is a close correspondence between simulated micro gases and measured data	Not specifying its specific impact on thermal comfort
[14]	Microclimate modeling of outdoor air temperature	Accurately predict the cooling load of green roofs	The parameter count during the modeling process is relatively high

From the above research, many scholars have analyzed different plant layout patterns. However, this research has mostly focused on the overall regional ecological environment and various ecological greening areas, and have not conducted more comprehensive research on urban street areas with relatively poor thermal comfort. In addition, previous research has focused on analyzing the impact of green plants on local climate, without delving deeper into the effects of local climate change on thermal comfort. This may be because there are many factors that affect thermal comfort, and existing research only considers the impact of changes in one or two factors during the analysis process, thus failing to comprehensively analyze the impact of climate change on thermal comfort. Therefore, based on the performance advantages of ENVI-met in microclimate simulation, this study innovatively applies it to simulate microclimate conditions of urban streets under different green plant arrangements. Based on the simulation results, the Predicted Mean Vote-Predicted Percentage of Dissatisfaction (PMV-PPD) is combined to evaluate the thermal comfort of street areas. PMV-PPD can take into account multiple factors such as human metabolic rate, environmental temperature, relative humidity, wind speed, and clothing thermal resistance in the evaluation process, in order to further optimize the green plant layout model of urban streets, improve the environmental quality of urban streets, enhance thermal comfort, and create a more livable working and living environment.

The innovation of this study is as follows. Regarding the impact of green plant layout on the thermal comfort of urban streets, the ENVI-met model is innovatively used to simulate the effects of different green plant arrangement schemes on climate factors. Subsequently, PMV-PPD is used to comprehensively evaluate the impact of simulated different green plant layout schemes on thermal comfort, in order to analyze the influence of green plant layout schemes on regional climate environment more accurately and provide effective reference for local climate environment analysis.

2 Second section

This section first measures the actual climate factors of Street A and designs different green plant layout schemes. Based on these measurement data, the impact of different green plant layout schemes on the thermal comfort of the street area in the city is simulated. Finally, the PMV-PPD index is applied to evaluate and analyze the thermal comfort of the area, in order to explore a more reasonable urban green plant layout plan.

2.1 Design of green plant layout

Thermal comfort is a person's subjective thermal sensation for the surrounding environment, influenced by individual psychology, body, and external environment. When simulating thermal comfort, the first step is to analyze the climate change conditions in the region. The regional climate formed by differences in vegetation, terrain, architecture, etc. within a certain area is called microclimate [15]. Greening plants are one of the essential elements in urban construction, playing a key role in regulating the microclimate and environmental quality of local areas. At the same time, the green plants arranged around urban streets can effectively improve air humidity, absorb solar radiation, and adjust urban temperature, thereby adjusting the perceived thermal comfort of the human body. The relationship among thermal comfort, green plants, and microclimate is shown in Figure 1 [16].

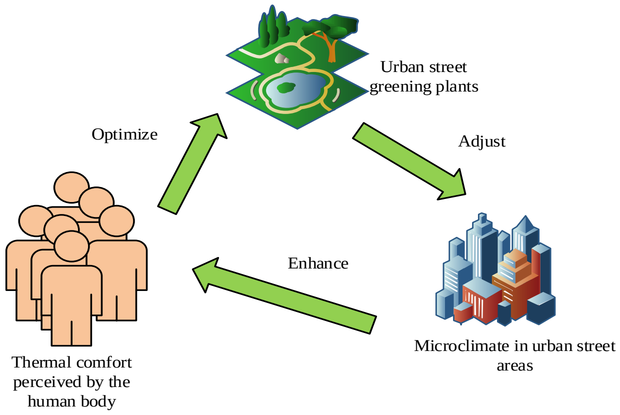

Figure 1: The relationship among thermal comfort, green plants, and microclimate.

As shown in Figure 1, urban green spaces have a regulating effect on regional microclimate. The regulated regional microclimate can effectively improve human thermal comfort, while thermal comfort can continuously optimize the urban green space environment. The combined effect of the three ensures a livable natural environment. Greening plants have a significant improvement effect on local microclimate. Specifically, different types of plants and their layouts can also have an impact on local micro-climates. The study selects climate data from Street A for simulation analysis. The street has a wide variety of green plants and a large green area, which can meet the simulation planning of green space layout. Firstly, the actual meteorological conditions in the area are measured using the PC-5 ultrasonic weather station produced by Jinzhou Sunshine Meteorological Technology Co., Ltd. to measure the actual wind speed, temperature, humidity, and solar radiation in the area. This device is equipped with independent power supply and support structure, which can be moved to any outdoor environment for measurement. Micro-climate changes near the ground are more significant. Therefore, the height of the device is adjusted to 1.5 meters and measurements are taken at three different locations. The study selects actual meteorological data measured on June 22, June 23, and June 24, 2022 as data samples to facilitate subsequent data simulation. The above analysis of actual temperature, humidity, wind speed and other data near the area provides sufficient data conditions for the climate simulation of the street.

After completing the actual data measurement, different green plant schemes are designed for analysis, in order to explore the impact of green space layout patterns on the thermal comfort of the area. Different plant species can affect the microclimate of a local area. The vertical structure of vegetation in that region generally includes the arbor layer (>300cm), shrub layer (50cm-300cm), and ground cover layer (<50cm). Four different vegetation layout types are designed, including arbor-shrub-ground cover (Scheme 1), arbor-ground cover (Scheme 2), shrub-ground cover (Scheme 3), arbor-shrub (Scheme 4), and control group (measurement data), to monitor local changes in thermal comfort. During monitoring, the influence of other meteorological factors is ignored. The vegetation community design scheme is shown in Table 2.

Table 2: Design of different green plant layout schemes

Scheme	Greening vegetation structure	Main plants	Average plant distance/cm
Scheme 1	Arbor-shrub-ground cover	Padus virginiana; Juniperus formosana; Ophiopogon bodinieri Levl.	350
Scheme 2	Arbor-ground cover	Magnolia grandiflora L.; Ophiopogon iaponicus Ker-Gawl.	300
Scheme 3	Shrub-ground cover	Rose chinensis; Ophiopogon bodinieri Levl.	300
Scheme 4	Ground cover	Iris tectorum Maxim.	/
Control group	Measured data	Magnolia grandiflora L.; Rose chinensis.	300

The above four schemes of green plants are designed to analyze their impacts on thermal comfort. Simulation schemes are designed based on measured results for comparison. Vegetation density refers to the number of plants planted per unit area. Green plants are uniformly planted in a rectangular area of 20×20. An average plant distance of 3m is designed to explore the impact of various green plant arrangements on thermal comfort.

2.2 Construction of microclimate simulation model based on ENVI-met

Based on the above measurement results and simulation schemes, in order to specifically analyze the impact of the layout pattern of street vegetation on thermal comfort, the ENVI-met model is applied to simulate and analyze local climate change, which is based on fluid mechanics and thermodynamics related research. Compared with other fluid dynamics simulation methods, this simulation method combines the actual environment of buildings, water bodies, plants, etc., making the results more reasonable. The basic structure of ENVI-met is shown in Figure 2 [17].

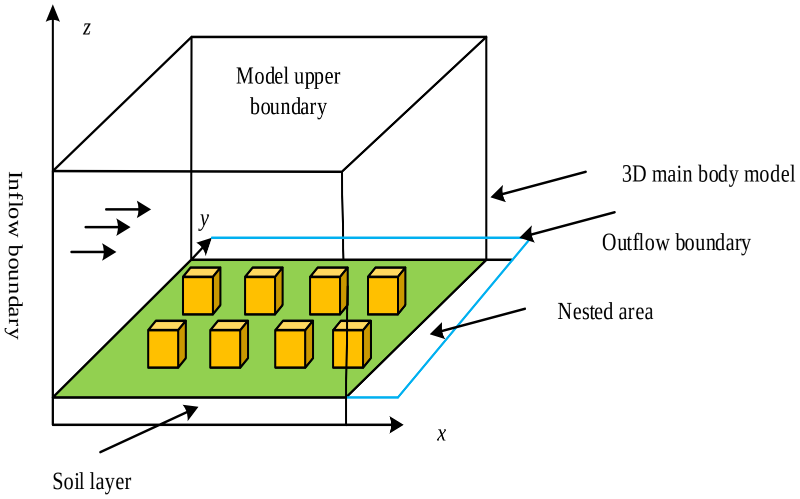

Figure 2: Basic structure of ENVI-met.

The ENVI-met can determine the simulated three-dimensional scale through the X, Y, and Z axis values of the three-dimensional coordinate system. The specific geographical location of the simulation is determined based on the simulated city selected by the software during setup. When using this model for analysis, building materials can be selected according to the actual situation, such as concrete, metal, brick walls, and other different materials. For plant layout, relevant parameters are set according to the required plant parameters such as tree height, trunk diameter, crown width, root density, etc., and try to fit the actual research conditions as much as possible. When using the ENVI-met to simulate local climate, it can be completed from five steps. Firstly, the geographical location and the relevant parameters such as the 3D data of the model are set. Then, in the working interface of the ENVI-met model, the time, duration, initial temperature, humidity, wind speed, and other boundary environmental conditions that need to be simulated are set. Then, various human body parameters are set to simulate thermal comfort. Next, after checking the established model file and boundary conditions, the model can be run. Finally, the simulation results are output. To better represent the changes in temperature and airflow in the ENVI-met model, the dynamic properties of the fluid are analyzed as shown in equation (1).

$$\frac{\partial p}{\partial a} + \rho g = -\frac{\partial (p - p_s)}{\partial a} + (\rho_1 - \rho) g \quad (1)$$

In equation (1), a represents the direction of air flow. ρ represents fluid density, m^3/s. ρ_1 represents external atmospheric density. p represents air pressure. p_s represents the air pressure at the s location. g represents the gravity. The airflow can be described by the steady-state equation (2).

$$\nabla \cdot (\rho u \varphi - \phi \nabla \varphi) = S_{\varphi i} + S_{\varphi} \quad (2)$$

In equation (2), φ represents variable flux. ϕ and $S_{\varphi i}$ are the diffusion coefficients corresponding to the variable φ and the internal source phase inside the fluid i, respectively. u represents the air component. ρ represents fluid density, m^3/s. S_{φ} represents the internal source phase of the fluid. The boundary conditions represent the influence of the environment near the truncated position in the simulation area. Due to the interference of ground friction, the wind speed near the ground area will produce a vertical gradient change, forming a gradient wind [18]. Gradient wind can be used to describe the atmospheric boundary. If the atmospheric boundary is considered as a linear approximation area, the wind speed variation in this part is shown in equation (3).

$$\frac{U(z)}{u} = \frac{1}{k}\ln(\frac{z+z_0}{z_0}) \quad (3)$$

In equation (3), u represents the frictional velocity. k represents the Karman constant, usually taking a value of 0.4. z_0 represents the rough of the ground. z represents the wind speed near the ground area. The wind speed at any height is obtained by calculating the exponential relationship between the wind speeds at the reference height, as shown in equation (4).

$$u_z = u_r(\frac{z}{z_r})^{\alpha} \quad (4)$$

In equation (4), u_z represents the wind speed at a height of z. u_r signifies the reference height, m/s. z_r represents the wind speed at the reference height. α represents the roughness index of the ground. The larger α indicates the higher roughness of the ground, and it generates greater resistance to wind speed. According to the general power exponent of wind speed gradient distribution, α is 0.3. Relying on actual parameters of Street A, the initial parameter settings of the ENVI-met model are shown in Table 3.

Table 3: Initial settings of ENVI-met

Content	Parameter	Value
Study area	Geographic location	112.06E, 36.25N
	Ground roughness	0.01
Study time	Start time	June 22, 2022
	End time	June 24, 2022
	Simulated time interval (h)	1h
Meteorological condition	Wind speed at a distance of 5m from the ground (m/s)	1.01
	Wind direction	Southwest wind
	Initial air temperature (℃)	31.45
	Relative humidity (%)	56.02

The geographical location, building distribution, and other related data of the area are obtained from the meteorological data network of the area. The solar radiation of the model is calculated based on geographical coordinates, and the cloud cover during the simulation period is set to 0. A database is constructed based on temperature, humidity, wind speed, solar radiation, and other data during the measurement period. The plan of the area is drawn, including buildings, roads, green areas, etc. near the street. ENVI-met is a three-dimensional model modeled in space based on field survey data and satellite image information. The number of grids for street green spaces is $182 \times 66 \times 10$, with cells of $2\text{m} \times 2\text{m} \times 4\text{m}$. The designed simulation model has grids of $440 \times 360 \times 53$ on the X, Y, and Z axes, with a grid accuracy of 2m in the X and Y directions and 4m in the Z axis direction. This is because the vertical height of the model should be at least twice that of the highest building being simulated. The building material in the model is concrete. The plants are selected from three categories: shrubs, trees, and ground cover. The common height of trees is between 2m-6m, the common height of shrubs is between 1m-4m, and the ground cover plants are generally below 0.5m.

2.3 Construction of thermal comfort evaluation model based on PMV-PPD model

After constructing a local microclimate environment simulation model, the thermal comfort can be analyzed based on the model simulation results. The comfort of outdoor environment is influenced by various factors, including not only the thermal environment in terms of climate, but also light conditions, sound environment, cleanliness level, etc. Therefore, the content included in comfort evaluation is diverse. The evaluation of outdoor thermal comfort is mainly based on climate factors, including temperature, wind speed, and humidity. The study uses the PMV-PPD to evaluate the impact of vegetation arrangement on thermal comfort [19-20]. This model defines outdoor comfort conditions that can make the vast majority of people feel comfortable, including four environmental variables and two human variables, taking into account human physiological conditions. The PMV is displayed in equation (5).

$$PMV = (0.303 * \exp(-0.036M) + 0.0275)Q \quad (5)$$

In equation (5), M signifies the metabolic rate of the human body, W/m^2. Q represents the energy transfer efficiency. The thermal comfort sensation corresponding to PMV is displayed in Table 2. The recommended values for PMV in thermal comfort standards are [-0.45, +0.5]. Equation (6) displays the PPD.

$$PPD = 100 - 95\exp[-(0.0335PMV \&\sup 2 + 0.2179)PMV \&\sup 2] \quad (6)$$

When the PMV value approaches a more comfortable environment, the PPD value decreases. Conversely, when PMV approaches colder or hotter environmental conditions, the PPD value increases. The relationship between PMV and PPD is shown in Table 4.

Table 4: The relationship between PMV and PPD

Thermal comfort feeling	PMV value	PPD value
Scorching	+3	100%

Heat	+2	75%
Slightly warm	+1	10%
Moderate	0	5%
A bit cold	-1	10%
Pleasantly cool	-2	75%
Cold	-3	100%

From Table 4, the relationship between PMV and PPD shows a downward concave curve. As the PMV value gradually decreases, the PPD value also gradually decreases. When it reaches the critical value, it is the most suitable thermal comfort for the human body. If the value exceeds the critical value, the human body feels overheated. If it is lower than the critical value, it indicates extreme cold.

3 Results

Based on the above analysis of the impact of different vegetation layout schemes on microclimate in the region, the simulation results are analyzed, namely temperature, humidity, and wind speed involved in thermal comfort. Then, PMC-PPD is applied to assess the perceived thermal comfort.

3.1 The influence of different plant arrangements on temperature, humidity, and wind speed

The experiment is conducted in a typical green area of Street A. Considering that different street floor materials have different reflectivity of solar radiation, which directly affects climate factors, this study explores the impact of green plant layout on urban street thermal comfort by analyzing different climate factors, including temperature, humidity, and wind speed. Firstly, Pearson correlation test is applied to analyze the correlation between various climate factors and PMV, as shown in Table 5. According to Table 5, there were different correlations between temperature, humidity, and wind speed and PMV. Among them, temperature was positively correlated with human thermal comfort, with a correlation coefficient of 0.895. The correlation between humidity and PMV was -0.642, and the correlation coefficient between wind speed and PMV was -0.557. From this perspective, improving air temperature is the most significant and effective way to increase thermal comfort.

Table 5: Correlation analysis between climate factors and PMV

Climate factors	Temperature	Humidity	Wind speed	PMV	PPD
Temperature	1	-0.462*	-0.562	0.895**	0.768**
Humidity	-0.568*	1	0.047**	-0.642**	-0.511*
Wind speed	-0.306	0.089	1	-0.557*	-0.246
PMV	-0.267	0.536*	-0.558*	1	0.879**

Note: "*" demonstrates significant correlation at the 0.01 level. "**" demonstrates significant correlation at the 0.05 level.

Based on the simulation results of different vegetation arrangements using ENVI-met and the actual results obtained from research, the temperature changes under different vegetation arrangements in the region are first statistically analyzed. Figure 3 displays the results. The average temperature of the control group was the highest, indicating that green plants had an improving effect on air temperature. Specifically, the average temperatures of the four simulation schemes were 26.58℃, 26.94℃, 25.03℃ and 27.31℃, respectively. It indicates that the arbor-ground cover has the best regulating effect on air temperature, followed by arbor-shrub-ground cover, shrub-ground cover and grass, which verifies the regulating role of greening plants in air temperature.

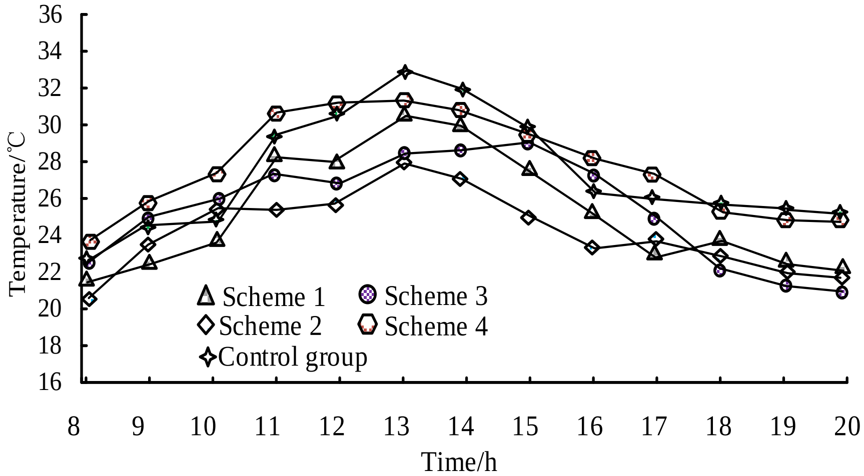

Figure 3: Temperature changes under different plant arrangements.

The humidity changes under different vegetation arrangements in the area at different ground heights are shown in Figure 4. Overall, the air humidity was relatively high under all four schemes. From the effect of increasing humidity, in Figure 4 (a), the average humidity of the control group was 52.02%, and the average humidity of the four simulated schemes were 79.56%, 67.58%, 64.23%, and 56.74%, respectively. In Figure 4 (b), the average humidity of the control group was 46.14%, while the average humidity of the four simulated schemes were 60.00%, 62.34%, 52.76%, and 49.85%, respectively. Among them, at 5m, the average humidity of scheme 2 exceeded scheme 1, which may be due to the influence of the monitoring point location, resulting in differences in air temperature and affecting air humidity. Overall, the humidity improvement effect of the arbor-shrub-ground cover (scheme 1) is relatively more significant. The combination of the three plants can play a better role in increasing humidity. The humidity effect at different heights is significantly better than other green plant layout schemes.

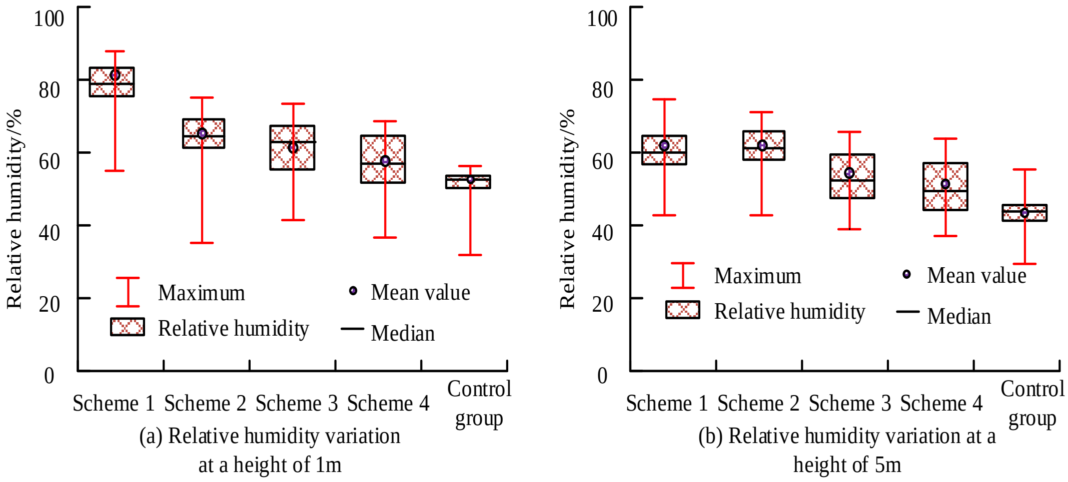

Figure 4: Changes in relative humidity under different plant arrangements.

Next, the study analyzes the changes in wind speed under different plant arrangements. The average wind speed on the test day is 1.5m/s, and the percentage change in wind speed at a specific moment is shown in Figure 5. The average daily wind speed for scheme 4 was 0.47m/s, scheme 1 was 0.98m/s, scheme 2 was 1.2m/s, and scheme 3 was 0.36m/s. Under the arrangement of shrub-ground cover green plants, the wind speed on that day was the lowest, which may be due to the obstruction effect of shrubs on wind speed under relatively low wind conditions. The impact of different schemes on wind speed was ranked in descending order of ground cover, arbor-ground cover, arbor-shrub-ground cover, and shrub-ground cover. The daily average wind speed under all simulation schemes is lower than that of the control group. Excessive or insufficient wind speed can affect thermal comfort. Appropriate wind speed can accelerate air circulation, alleviate high temperatures, and improve thermal comfort.

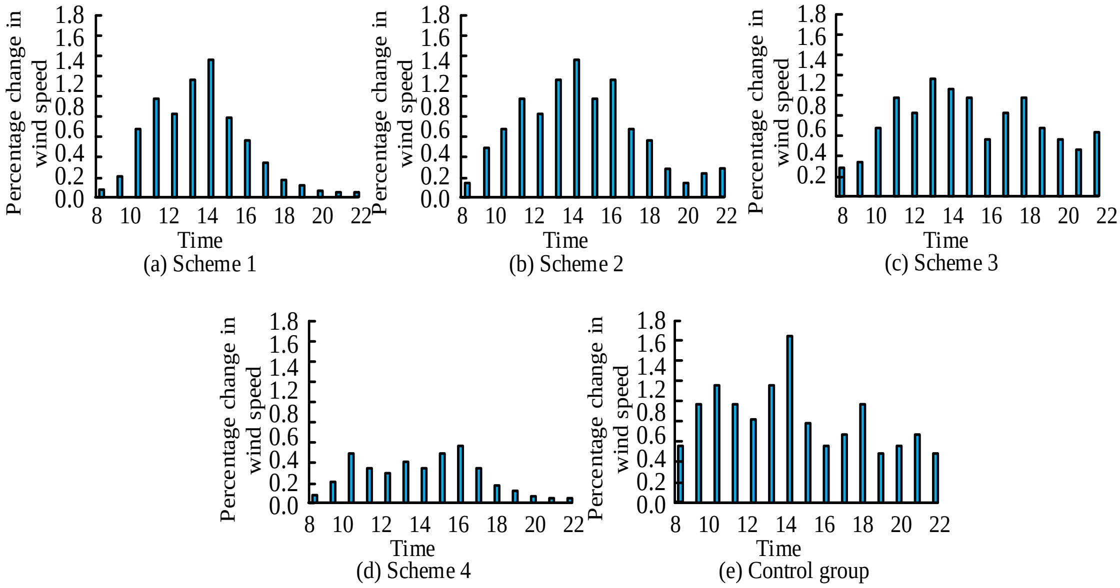

Figure 5: Wind speed changes under different test scenarios on the test day

3.2 Human thermal comfort analysis under different plant arrangements

The PMV-PPD changes in this area during the simulation are shown in Figure 6. As shown in Figure 6 (a), the PMV variation trends under all schemes were basically the same, and the differences were mainly manifested in the change intensity at different time points for each scheme. The daily average PMV values of the four different simulation schemes were 0.55, 0.71, 0.46, and 0.21, respectively. The daily average PMV value of the control group was 0.43. It was generally in a relatively hot state throughout the day, with temperatures only being relatively suitable around early morning. Among the four schemes, the regulating effect of ground cover plants (scheme 4) on human thermal comfort is not significant because the plant species are relatively short and have no shading effects. The other three schemes all have varying degrees of regulating effects. According to the PPD thermal comfort grading results in Figure 6 (b), except for scheme 4, all other simulation schemes showed good adjustment effects on thermal comfort. Among them, scheme 2 had the most significant thermal comfort adjustment effect, followed by scheme 1 and scheme 3.

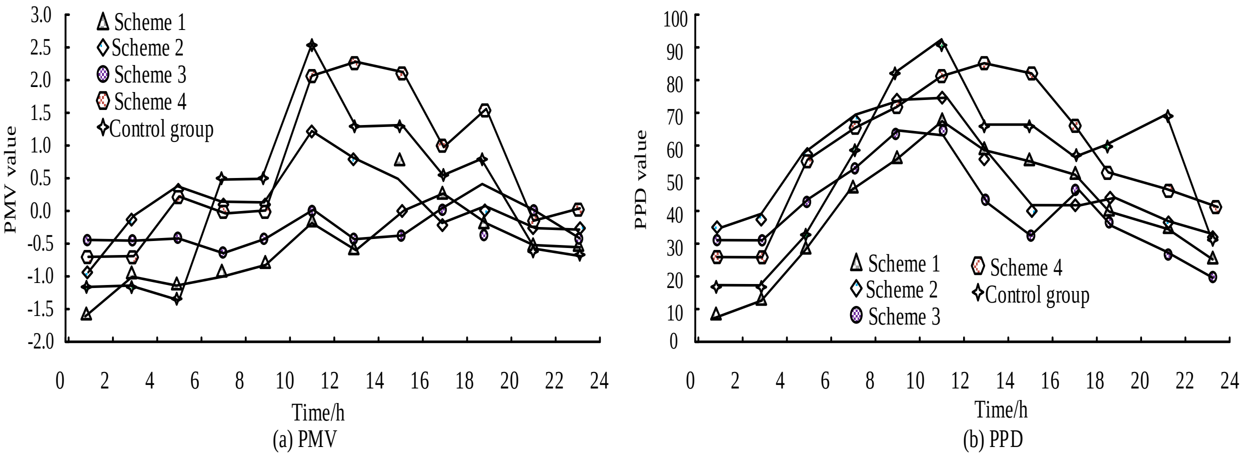

Figure 6: PMV-PPD values under different green plant arrangement schemes

Then, further analysis is conducted using the Munich Energy Balance Model for Individuals (MEMI). The results are shown in Figure 7. From Figure 7, there were significant differences in the improvement effect of different green vegetation arrangements on thermal comfort. The overall improvement effect showed an initial increase followed by a decrease. Before 11:30 in the morning, it basically showed an upward trend.

Between 11:30 and 16:00, there were fluctuations with different amplitudes, but all remained in a relatively high range. After 16:00, there was a sharp decrease and then gradually stabilized. The improvement effect of scheme 1 is consistently higher than other simulation schemes, indicating that the combination arrangement of arbor-shrub-ground cover plants can better improve thermal comfort.

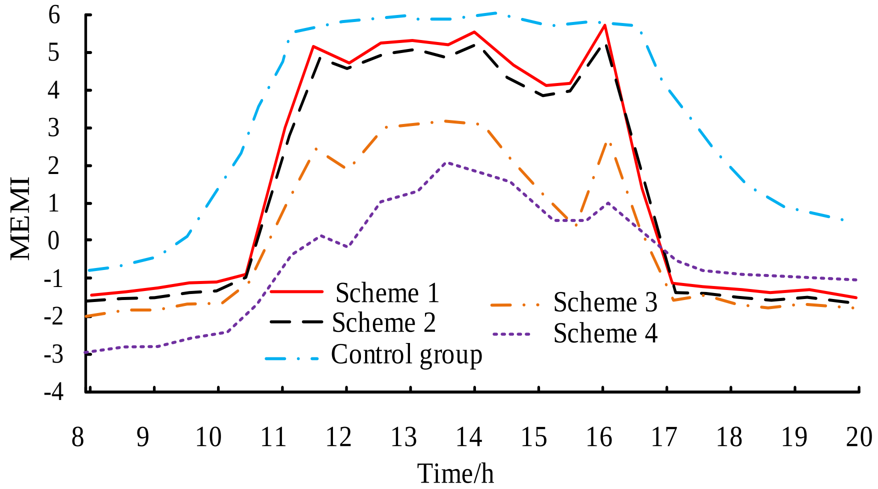

Figure 7: Thermal comfort evaluation of different plant arrangements based on MEMI

According to the results, the Root Mean Square Error (RMSE) is used to measure the deviation between the measured results and the simulation results, thus reflecting the simulation accuracy. Weighted Mean Absolute Percentage Error (WMAPE) is used to measure the quality of simulated prediction results. The error values calculated by RMSE and WMAPE demonstrate better simulation performance. According to Table 6, the simulation errors of different schemes were all below 4%, which was within a reasonable range. The simulation method designed in this study has high accuracy.

Table 6: Comparison of error in simulation results of different meteorological factors (%)

Content	Evaluation indicator	Scheme 1	Scheme 2	Scheme 3	Scheme 4
Temperature	RMSE	0.785	0.459	0.893	0.694
	WMAPE	1.357	1.462	1.689	1.227
Humidity	RMSE	3.012	3.245	2.946	2.758
	WMAPE	3.558	3.764	2.961	2.753
Wind speed	RMSE	1.264	1.032	0.987	1.471
	WMAPE	2.066	2.157	2.630	1.958

To further analyze the accuracy of the simulation results, the actual measured temperature, humidity, and wind speed during the measurement period are compared with the simulation results, as shown in Table 7. According to Table 7, the simulation results of scheme 3 had the smallest error compared with the actual results, indicating that the current green layout in the area was relatively close to scheme 3. The simulation method used in the study can effectively analyze the actual climate conditions, which is feasible. Comparatively speaking, under scheme 4, the simulation results obtained have better climate conditions, namely lower temperature, humidity, and wind speed, which are more suitable for human thermal comfort.

Table 7: Comparison between simulation results and actual results

Content	Actual value	Scheme 1	Scheme 2	Scheme 3	Scheme 4
Temperature	31.45	32.08	32.11	31.02	30.45
Humidity	56.02	54.01	58.42	55.74	54.36
Wind speed	1.01	1.62	1.27	0.98	0.86

Sensitivity analysis is conducted on the parameters used in the study to further validate the reliability of the method. The analysis results are shown in Table 8. From Table 8, plant density, layout dimensions, temperature, humidity, and wind speed all had relatively high sensitivity values, indicating that the above factors had a significant impact on thermal comfort. This is consistent with the simulation results obtained by changing the values of these parameters in the simulation scheme, which verifies the reliability of the research method.

Table 8: Results of the sensitivity analysis

Parameters	t	Sensitivity
Plant density	4.267	1.25
Layout dimensions	6.281	1.41
Temperature	10.345	1.92
Humidity	9.047	1.57
Wind speed	7.238	0.88

To verify the advantages of the research method in thermal comfort simulation, the study compares it with other commonly used methods, including Universal Thermal Climate Index (UTCI) or Standard Effective Temperature (SET*), Physiological Equivalent Temperature (PET), as shown in Table 9. According to Table 9, the evaluation method used in the study performed the best in different indicators. Its relative error, precision, total time, and stability were 0.04, 93.16%, 4.54s, and 88.59%, respectively. Compared with UTCI, SET*, and PET, the research method has better performance.

Table 9: Performance comparison of different methods

Methods	Relative error	Precision (%)	Total time (s)	Stability (%)
PMV-PPD	0.04	93.16	4.54	88.59
UTCI	0.18	81.35	6.78	76.23
SET*	0.14	75.93	5.36	80.39
PET	0.26	84.26	9.08	82.76

4 Discussion

To investigate the impact of green layout methods on thermal comfort, ENVI-met is used to simulate local climate and environmental conditions. Then, the PMV-PPD evaluation method is used to assess thermal comfort. The experimental results obtained showed that the ENVI-met simulation method performed well in the simulation analysis of various meteorological factors. The simulation results demonstrated the significant impact of different greening schemes on thermal comfort. The average temperature of ENVI-met simulation method in the four greening schemes was 26.58 ℃, 26.94 ℃, 25.03℃ and 27.31℃, respectively, which verified the regulating effect of greening plants in air temperature. The temperature difference is due to the higher canopy coverage and better shading effect of trees, resulting in relatively lower temperatures. In addition, the transpiration of different vegetation types varies, affecting air humidity and thus affecting temperature. Compared with the research of A et al., [21] the study explored more diverse green plant layout schemes, all of which showed basically consistent changes. The PMV values of different simulation schemes were basically consistent with the actual trend, with daily average PMV values of 0.55, 0.71, 0.46, and 0.21, respectively, verifying the effectiveness of this simulation method. In sensitivity analysis, plant density, layout dimensions, temperature, humidity, and wind speed all had relatively high sensitivity values because plant density and layout dimensions have varying degrees of impact on temperature, humidity, and wind speed, thereby affecting thermal comfort. According to the simulation results, the corresponding thermal comfort evaluation indicators obtained using the PMV-PPD method had high accuracy, with relative error, precision, total time, and stability of 0.04, 93.16%, 4.54s, and 88.59%, respectively. Compared with UTCI, SET*, and PET, the research method has better performance. Because this method takes into account multiple factors such as human metabolic rate, environmental temperature, relative humidity, wind speed, clothing thermal resistance, etc. in the evaluation process, and considers the influence of human body conditions and external environment, it is more in line with practical thermal comfort evaluation. Compared with the research designed by Mei Y et al. [22], this study adopted the PMV-PPD method, which comprehensively considered more influencing factors and effectively promoted the analysis of local climate environment.

5 Conclusion

In order to better design the green plant layout on urban streets and maximize ecological and environmental benefits, taking Street A in a northern city as an example, different green plant layouts were simulated. On the basis of the ENVI-met model, a microclimate simulation model for the study area was constructed. Then, the PMV-PPD evaluation index was applied to analyze the thermal comfort. The simulation results showed that temperature was positively correlated with human thermal comfort, with a correlation of 0.895. The correlation between humidity and PMV was -0.642, and the correlation coefficient between wind speed and PMV was -0.557. This indicated that relevant climate factors were significantly correlated with thermal comfort. The average temperatures of the four simulation schemes were 26.58℃, 26.94℃, 25.03℃ and 27.31℃, respectively, which indicated that the arbor-ground-cover had the best air temperature regulation effect, followed by arbor-shrub-ground cover, shrub-ground cover and grass, which verified the regulation role of greening plants in air temperature. The average humidity of the four simulated schemes was 79.56%, 67.58%, 64.23%, and 56.74%, respectively. The average daily wind speed for scheme 4 was 0.47m/s, scheme 1 was 0.98m/s, scheme 2 was 1.2m/s, and scheme 3 was 0.36m/s. Under the shrub-ground cover green plant layout, the wind speed on that day was the lowest, indicating that different green vegetation arrangements had varying degrees of impact on thermal comfort. Taking into account temperature, humidity, and wind speed conditions, the arbor-shrub-ground cover scheme can better integrate the effects of various meteorological factors on thermal comfort. However, there are still shortcomings in the research. In order to more accurately analyze the impact of green vegetation layout on thermal comfort, the influence of different ground conditions on meteorological factors has not been considered. In the future, the impact of different ground materials, such as the strength of permeability, on the green plant layout can be explored to analyze the effect on thermal comfort.

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