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Original Research

The Impact of Tree-Planting Location on the Microclimate and Thermal Comfort of the Micro-Public Space

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Abstract

This study considered Jindai Street in Huizhou, Guangdong, as an example to discuss the impact of different tree-planting locations on microclimate and thermal comfort in the micropublic spaces. The computational fluid dynamics software PHOENICS was employed to simulate the microclimate and thermal comfort of 5 different tree-planting locations, including the centre (CO), the southwest corner (SW), the northwest corner (NW), the northeast corner (NE), the southeast corner (SE) and with no trees (NT) in the site. The results showed that planting one tree can reduce the average air temperature at the pedestrian height (1.5 m from the ground) by 1.83~2.48ºC, increase the average relative humidity by 5.11~6.85%, increase the average wind speed by 0.15~0.29 m/s, and decrease the average UTCI by 1.63~2.30ºC. A tree planting on the southwest side has the best cooling effect in the afternoon. Planting one tree can significantly increase the air humidity no matter the planting location. Trees can have a better effect on improving ventilation when poorly ventilated at the site. The maximum UTCI drop was 3.35ºC under the tree canopy. The study clarified the microclimate and thermal comfort effect of tree-planting effects of different locations in the micropublic space.

Keywords: micropublic space, tree-planting locations, outdoor microclimate, thermal comfort, urban renewal

Introduction

The outbreak of COVID-19 is an alert for human beings. Whether the high-intensity urban development and construction or the lack of urban public open space will cause a series of environmental problems. In the process of urban development, leading to a series of environmental problems, many green ecological spaces were replaced by buildings and roads. Poor urban ventilation and the aggravation of heat islands affect people's quality of life, urban sustainable development, and even physical and mental health [1-3]. Therefore, it is urgent to reduce the density of urban buildings, increase public space, and improve the residential

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environment. In the 21st century, with the accelerating process of China's urbanization and the increasing shortage of land resources, the focus of urban planning has gradually shifted from increment to stock and decrement and from large-scale expansion to microscale space optimization and adjustment [4]. Additionally, the transformation of old communities in the central area of the old city has become an important part of urban planning. It has become an important measure to demolish illegal construction, build public green space, and create micro public activity spaces in old communities with high building density. Micropublic space, as a small outdoor public space for people to relax and communicate, which has a high density of distribution, convenient use and the closest connection with residents' daily lives, has attracted increasing attention [5, 6]. As part of the local climate, the microclimate of these micro spaces is closely related to people's lives and affects people's quality of life to a large extent [7, 8]. The old district plays an important role as the inheritor of urban history and culture. Most of the existing old districts are facing the problems of lacking activity space, poor sanitation, poor ventilation, and sweltering summer heat. How to transform these old communities to meet the needs of residents and improve the comfort of the human body is an urgent problem in current urban planning and construction.

In high-density urban areas, embedded green land is a very effective way to improve the microclimate [9]. Green land can effectively reduce the air temperature near the urban surface through shading and transpiration of plants [10-14]. Wind is also an important factor that directly affects residents' comfort. Vegetation can block the wind through the drag force, reducing the discomfort caused by excessive wind speed. Additionally, the pores of vegetation can also effectively ventilate to promote the diffusion of pollutants in the air [12, 13, 15]. The larger the green coverage area is, the lower the temperature and the higher the humidity at the site. The change in wind speed depends on the situation at the site [16-19]. However, when the area increases to a certain extent, the cooling effects on the environment will not change much [20]. Taking into account the actual situation of limited land resources, a large number of green spaces cannot be set up, and a reasonable plant layout is more practical than blindly increasing the green area [21, 22]. By analysing the environmental benefits of urban green space at home and abroad, Wei Bin and others have found that when the greening rate is less than 40%, changing the internal structure and spatial layout of the green space can have a great impact on the surrounding environment [23]. After that, Zölch and many other researchers also found that the air temperature, relative humidity, wind speed and thermal comfort of the human body would change if the horizontal layout of green space were changed [20, 24-26]. Changes in the vertical structure of green spaces also have an impact on the microclimate. The research results of researchers such as Sodoudi and Potchter have shown that in the summer daytime, trees have a more obvious effect on lowering air temperature than shrubs and grasses, and they help to improve environmental comfort. This is because tree transpiration absorbs more heat from the surroundings, promotes airflow, improves ventilation and provides shade with a large canopy [25, 27]. Additionally, the growth characteristics of trees themselves, such as canopy size, canopy shape, leaf area index, and canopy porosity, all have impacts on microclimate and thermal comfort [28-30]. Tree planting not only plays an important role in improving the microclimate in summer but also forms different activity spaces due to their growth characteristics [31]. A large number of researchers at home and abroad have conducted research on the cooling effect of trees in different climate zones, and they found that it varies in different climate zones [32].

Hot and humid regions are facing outstanding thermal comfort problems in summer. In the reconstruction of old urban areas in these regions, planting trees in micropublic spaces will reduce the ambient air temperature through shading and transpiration. Additionally, it will increase the air humidity due to transpiration. Will it contribute to the improvement of environmental comfort and to what extent? Will choosing different tree-planting locations affect the improvement and to what extent? The answers to the above questions will help enrich the theory of landscape architecture design and will also foster the improvement of the residential environment in the transformation of old urban areas. This study aimed to explore the impact of different tree-planting locations on the microclimate (including air temperature, relative humidity, and wind speed) in the micro space of high-density urban areas in summer. Through the evaluation indicators of thermal comfort, this study analysed the thermal comfort of different planting locations in the site and obtained the optimal planting location from the perspectives of microclimate and thermal comfort to provide a theoretical basis for the design of micropublic space in urban transformation.

Experimental

Research Area and Research Object

The study area is located in Jindai Street, Huizhou, Guangdong (114.399°E, 23.091°N). Huizhou is located in the Pearl River Delta city cluster in southeastern Guangdong Province (Fig. 1). It belongs to a hot summer and warm winter area, with high temperature, high humidity and heavy rainfall in summer, which is a typical hot and humid area. Huizhou has a subtropical

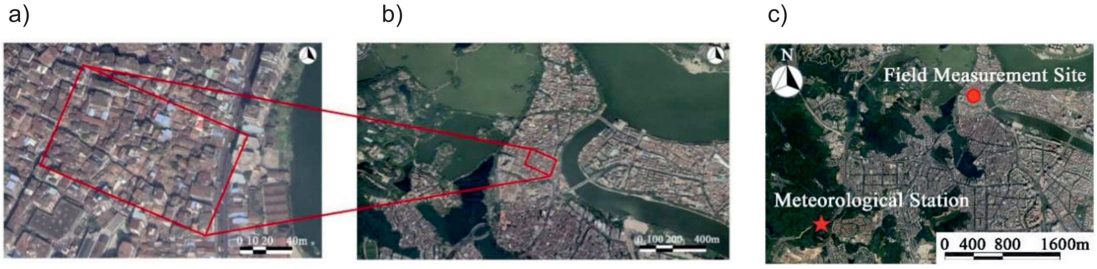

Fig. 1. Field measurement site: a) study area; b) study area and its surroundings; c) location of the field measurement site and meteorological station.

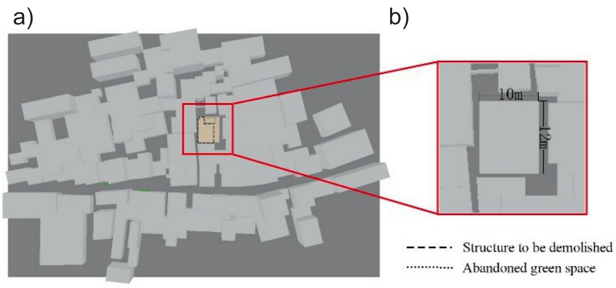

Fig. 2. The formation of micro space: a) the construction to be demolished; b) the size of micro space.

monsoon climate, with southeasterly winds prevailing in summer. Jindai Street was built in the 22nd year of Hongwu in the Ming Dynasty (1389) and is one of the "Nine Streets and Eighteen Alleys" in Huizhou. The block is adjacent to West Lake, a famous 5A-level scenic spot in Huizhou. The current land use function is complex, mainly for residence, combined with other functions such as commerce. The blocks are facing problems of ageing facilities, dilapidated houses, high building density, poor environmental quality, and lack of public space for residents. Therefore, it is an important measure for the Huizhou government to form micropublic space through reconstruction and improve the environment of Jindai Street and people's livelihood.

Combined with on-site investigation, we chose a residential area in the middle of Jindai Street as the research area. There was an illegal construction here. Two small roads passing by on the north and south sides of the house served as the passages for residents to ride through. The plan intends to retain the existing surrounding roads. We supposed to demolish the illegal construction to build a micro space with a length of 12 m from north to south and a width of 10 m from east to the west in the urban renewal (Fig. 2).

Field Measurement and Model Verification

To verify the accuracy of the model, the two main factors affecting the outdoor microclimate model, temperature and wind velocity, need to be measured and compared with the simulation results. The time interval 11:00-15:00 on September 20, 2019, representing the typical hot and humid climate characteristics of Huizhou, was selected to carry out the field measurements. Based on the difference in shading conditions, surface coverage and the positional relationship with plants in the Jindai Street study area, 10 sampling points were selected to record the temperature and wind speed at the site using a kestrel 5500 hand-held meteorological instrument. The sensors used for monitoring presented the following characteristics:

– The accuracy of the measured temperature was ±0.4ºC.
– The accuracy of the wind velocity was ±1.04% within the airspeed range of 3.59 to 19.93 m/s.
– The accuracy of the wind velocity was ±1.66% within the airspeed range of 0.85 to 3.59 m/s.
– The response time of the sensors was 2 s.

The recording frequency was once every 10 s. The dominant wind of the day was northerly. To avoid the influence of the building on the wind direction and speed, a monitoring point (point 10) was set at 1.5 m above the building on the roof of the highest building (26.2 m high) around the site in the upwind direction of the incoming wind, and the relevant meteorological data were recorded. Other monitoring points were located at the site, 1.5 m from the ground (Fig. 3).

Referring to the setting of the calculation domain in the COST manual and AIJ [33, 34], to ensure the complete convergence of the model, according to the size of the model: 178 m * 116 m * 24 m (length, width and height) (Fig. 4b, c), the sizes of the XYZ axis of the calculation domain are set as 1300 m * 1300 m * 120 m (Fig. 4a, c). The grid in the model was 1 m×1 m (Fig. 4b), and the rate of change with the surrounding environment was 1.08 (Fig. 4a). The physical model of the site was constructed and simplified. The improvement in microclimate was significant at 14:00, when temperature was the highest of the day [35]. The meteorological data of the day observed at 14:00 at Huizhou Meteorological Station, 4 kilometres southwest of the measured site, were used as the input conditions for atmospheric pressure, temperature and humidity (Fig. 1c). By analysing the measured data 10 minutes before and after 14:00 at monitoring point No. 10, it was determined that the wind direction at 14:00 on that day is north wind. According to the measured wind speed, the wind speed at a relative

Fig. 3. Distribution of measured points. a) Study area and model area; b) field measurement site; c) pictures of the monitor site.
Note: 1) Three points are located in the downwind direction of the plant, No. 3 is located on the pavement and under the shade of the trees; No. 8 is located on the pavement, next to the shrubs, in the shadow of the building; Point 6 is located on the lawn, next to small trees, in the sun; 2) Three points are located on the pavement within the block: No. 4 is in the sun, No. 9 is in the shadow of the building; No. 5 is located near the entrance of the lane in the direction of the incoming wind; 3) Three points are located on the pavement inside the lane: No. 1 is located at the entrance of the lane in the direction of incoming wind; No. 2 is located in the shadow of the building in the alley; No. 7 is in the lane in the sun.

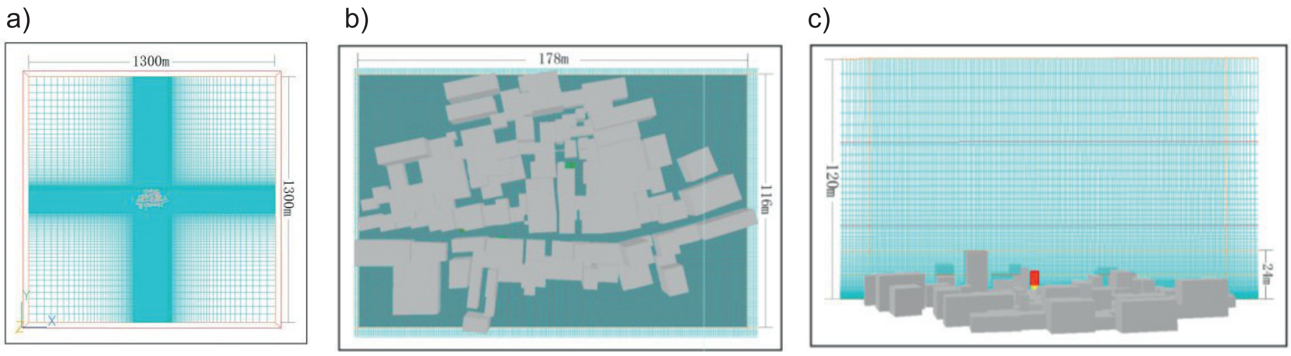

Fig. 4. Grid distribution in the computational domain: a) Global grid distribution on the plane in the computational domain; b) Grid distribution on the plane of the model; c) Grid distribution of vertical space in the computational domain.

height of 10 m was obtained as the wind speed input value through exponential rate conversion. The input boundary conditions of the model are shown in Table 1, and the pavement and building material parameters of the model are shown in Table 2 [36-38].

Comparing the measured value with the simulated value, it can be seen that the temperature difference of all points was between 0.01℃ and 0.63ºC except point 9 (Fig. 5a). The measured temperature of No. 9 was significantly different from the simulated temperature because it is outside the door of a household. Residents return home at approximately 2 PM and leave the door open, resulting in convection between the cold air cooled by the air conditioner inside and the air around monitoring point No. 9, which reduces the air temperature. Except for point 1, the difference in wind speed at other points was between 0-0.23 m/s (Fig. 5b). Due to the close distance to the wall, point 1 was greatly affected by the turbulence generated by the wall, which reduces the wind speed. Therefore, compared with the simplified simulation model, the wind speed was smaller. Fig. 6 is the scatter plot of simulated and measured air temperature and wind speed. From the linear regression equation of temperature (Fig. 6a) and wind speed (Fig. 6b) ($y = 0.8228x + 5.6812$; $y = 0.7931x + 0.0741$), it can be seen that the measured value fits well with the simulated value. According to the goodness of fit R^2 of temperature and wind speed, they were 0.7695 and 0.8257, respectively. Therefore, this model was reliable and can be applied to the study of microclimate in summer micropublic space.

Simulation Model

Setup of the Simulation Model

The computational domain and grid of the simulation model are consistent with those of the measured verification model. The meteorological conditions at 14:00 on September 19, 2017, were taken as the input parameters of the model, which were

Table 1. Input boundary conditions of the CFD measured model.

Parameters	Inputs
Simulation date	September 20, 2019
Simulation time	2:00pm
Latitude	23°09′N
Radiation Flux Model	IMMERSOL
Turbulence Model	RNG – kε
Ground roughness	$\alpha = 0.22$
Atmospheric pressure	95580 Pa
Air temperature	31.5ºC
Relative humidity	41%
Wind direction (N = 0, E = 90)	N (0º)
Wind velocity (10 m)	1.319 m/s
Model deflection angle (The angel between N (0°) and Y axis)	32°

Note: According to the logarithmic function $u_z = u_R \left(\frac{z}{z_R}\right)^{\alpha}$, the gradient wind in the atmospheric boundary layer is the surface roughness index. In this study, V_0 = 1.65 m/s, Z0 = 27.7 m, and Z = 10 m. The study area is located in an urban area with a high density of buildings, and the value of α is 0.22 [39].

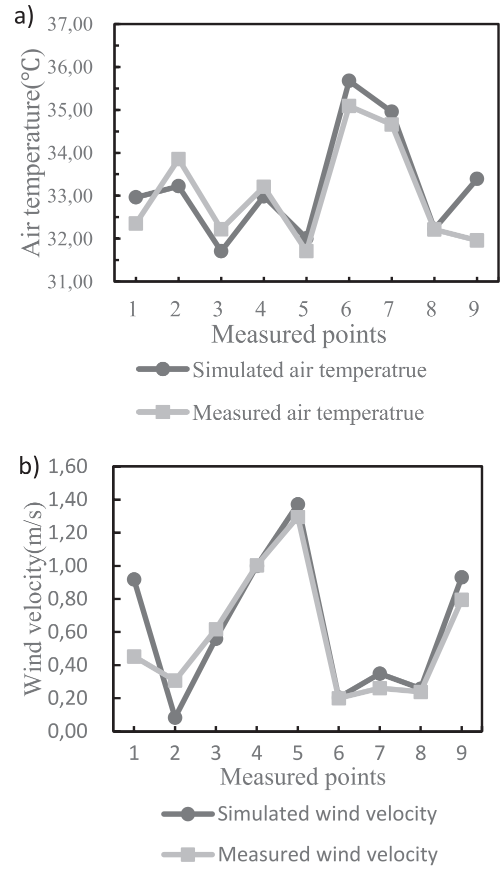

Fig. 5. Comparison of measured and simulated values: a) air temperature and b) wind velocity.

in line with the meteorological conditions of typical meteorological days in Zone IV of the China Building Climate Zoning Map where the study area was located [40]. The adjustment of the microclimate is of great significance at 2 p.m. when the temperature reaches its highest point of the day. The input boundary conditions of the scheme model are shown in Table 3. The setting of material parameters is consistent with the simulation model (Table 2).

Simulation Scheme

Referring to the conventional design scheme, the ground of the micropublic space in the model was set as pavement made of bricks. Five schemes with different tree-planting locations and one with no tree planting as the control group were set, and six simulation schemes were set (Fig. 7). Among them, NT was

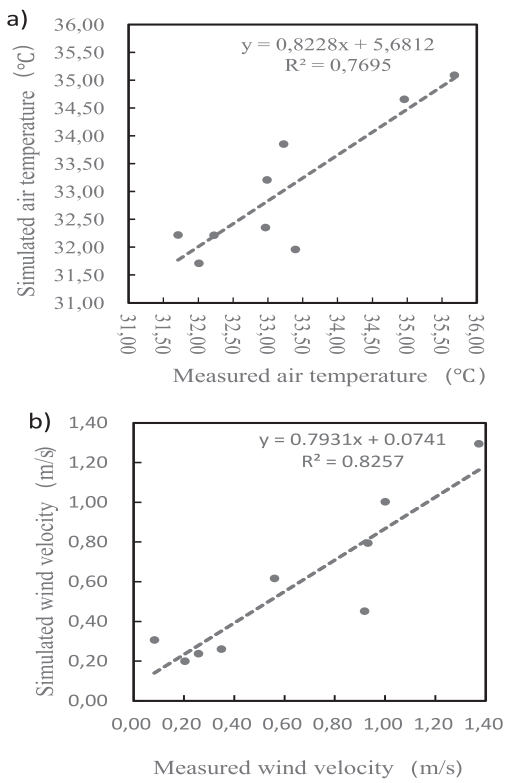

Fig. 6. Scatter diagram comparing measured and simulated values: a) air temperature b) wind velocity.

Table 2. Pavement and building material setting.

Parameters	Inputs
Wall function law for pavement	Fully rough
Emissivity for pavement	0.90
Solar absorption for pavement	0.74
Wall function law for buildings	General log law
Emissivity for buildings	0.90
Solar absorption for buildings	0.50

Table 3. Input boundary conditions of the scheme model.

Parameters	Inputs
Simulation date	September 19, 2017
Simulation time	2:00 pm
Latitude	23°09′N
Radiation Flux Model	IMMERSOL
Ground roughness	$\alpha = 0.22$
Atmospheric pressure	99670 Pa
Air temperature	32.3ºC
Relative humidity	57%
Wind direction (N = 0, E = 90)	SE (136°)
Wind velocity (10 m)	1.90 m/s
Model deflection angle (The angel between N (0°) and Y axis)	32°

Table 4. Comparison of microclimate for different tree-planting schemes.

Scheme	Air temperature (ºC)	Relative humidity (%)	Wind speed (m/s)
NT	36.27	45.73	0.29
CO	33.85	52.45	0.50
SW	33.79	52.58	0.49
NW	34.42	50.84	0.58
NE	34.44	50.89	0.44
SE	34.00	51.98	0.49

for the site without trees; CO was for trees planting in the centre of the site, SW was for trees planting in the southwest corner, NW was for trees planting in the northwest corner; NE was for trees planting in the northeast corner; and SE is for trees planting in the southeast corner. White orchid, a common tree species in Huizhou City, was selected as the tree species. The parameters of the trees in each scheme were exactly the same. The tree height was 12 m, branch point height was 2 m, crown width was 6 m, leaf area index was 3.5, transpiration rate was 0.012 g/(m)²/s) [41-43]. The common brick pavement in the area was selected as the ground pavement material. The solar radiation absorption coefficient was 0.75, the specific heat capacity is 840 J/(kg · K), the material density was 1600 kg/m^3 and the thermal conductivity was 0.69 w/(m · K).

Results Processing

The cloud images and average values of the simulation results of air temperature, relative humidity, wind speed, wind direction and thermal comfort (UTCI) at a height of 1.5 m for six simulation schemes were output to explore the impact of different planting locations of trees on micro space microclimate and thermal comfort. The difference value of the UTCI was also calculated.

Results and Discussion

The Impact of Tree-Planting Location on the Average Air Temperature, Relative Humidity and Wind Speed of the Site

The average air temperature, humidity and wind speed can represent the characteristics of the overall microclimate of the site. Table 6 shows that the average air temperature of the site without trees was the highest, and the cooling effect of trees in different planting locations on the site is in descending order: SW, CO, SE, NW and NE, and the cooling range of the SW scheme can reach 2.48ºC. The average air temperature of the three planting locations, SW, CO, and SE, was not much different (the difference between SW and SE was 0.15ºC). Therefore, regardless of where the tree is planted, it has a cooling effect at a height of 1.5 m on the site. Tree planting on the south, west or middle of the site has a better overall cooling effect than on the north and east. Compared with the scheme without trees, the planting of trees increased the average relative humidity at the site. The relative humidity in the SW and CO schemes increased more than that in the other schemes, reaching more than 6.5%, followed by the SE scheme. The planting in the northeast and northwest had the least effect on the increase in relative humidity. Compared with the NT scheme, tree planting increases the average wind speed at the site, of which the maximum increase in wind speed is 0.29 m/s (NW scheme). Although the planting of a tree may block the airflow, for relatively closed high-density urban built-up areas, the shadow area formed by the canopy and the periphery will produce an air thermal difference,

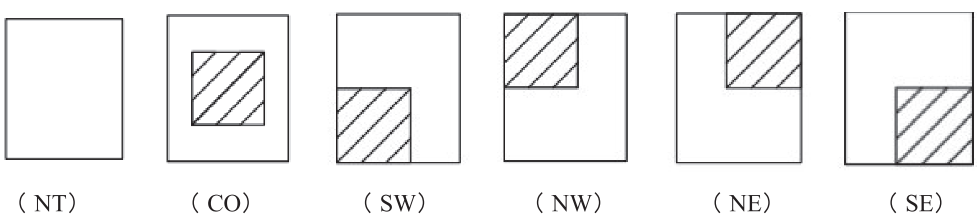

Fig. 7. Plan of tree-planting simulation scheme and modes.

which promotes airflow and improves the ventilation conditions of the site.

The Impact of Tree-Planting Location on the Distribution Characteristics of Air Temperature at the Site

In the NT scheme, the temperature on the west side of the site is higher than that on the east side. The planting of trees has changed this temperature distribution, especially in the CO and SW schemes; the overall temperature distribution of the site has the opposite characteristics (Fig. 8). Except for the SE scheme, the lowest temperatures of the other schemes are under the tree. As there were no trees (NT scheme), the southwestern part of the site was affected by the surrounding environment, and the temperature was higher than that in other areas. After the trees are planted, the trees reduce the air temperature at the pedestrian height through shading and transpiration. A large pressure difference was formed between the air of lower temperature under the tree with the high-temperature area in the northwest, which promoted the flow of cold air to the southwest. The temperature of the air and the northwestern high-temperature area formed a large pressure difference, which promotes the flow of cold air to the southwest. Therefore, the lowest temperature in the SE scheme was located slightly to the west under the tree. This showed that the thermal difference will promote local airflow and change the air temperature distribution characteristics.

Combined with the wind direction distribution map (Fig. 9), it can be clearly seen that the air at the pedestrian height on the site flows from under the trees to the periphery. In the NW and NE schemes, the lower temperature at the site is only concentrated in a small area north of the site, where the cooling effect of trees is weakened due to convection between the hot air from the alley and the cold air under the trees in the middle of the site. This shows that the airflow from outside may play a leading role in the case of good ventilation, and the convection effect caused by thermal difference is limited.

Therefore, if the trees are planted in the micro space on the cooler side of the original site and in the upwind direction, the airflow generated by the thermal difference formed by the cooling effect of the trees will work together with the external wind and can provide the best cooling effect in the downwind direction of the site. If the trees are planted downwind from the direction of the wind, the cooling effect of the trees in the upwind direction is limited, and if there are obstructions such as buildings in the downwind direction, the cooling effect range will be reduced. If the trees were planted in the downwind direction from the direction of the incoming wind, the cooling effect of the trees on the upwind direction was limited, and if there were obstructions such as buildings in the downwind direction, the cooling effect will be reduced.

Fig. 10 shows the maximum, minimum and average values of air temperature at the 1.5 m height at the site under the six schemes, as well as 25%-75% of the air

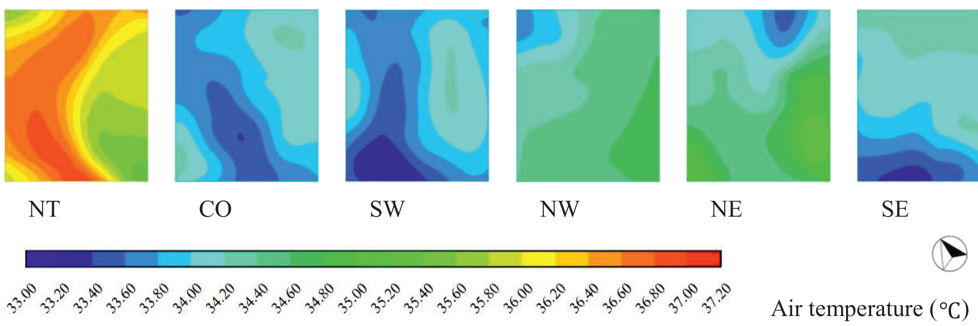

Fig. 8. Air temperature distribution at pedestrian height (1.5 m above the ground) of different tree-planting schemes.

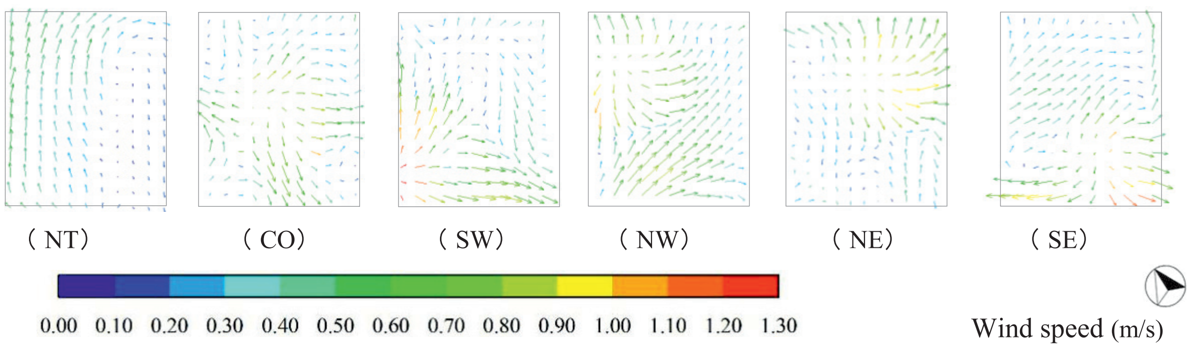

Fig. 9. Wind direction distribution at pedestrian height (1.5 m above the ground) of different tree-planting schemes.

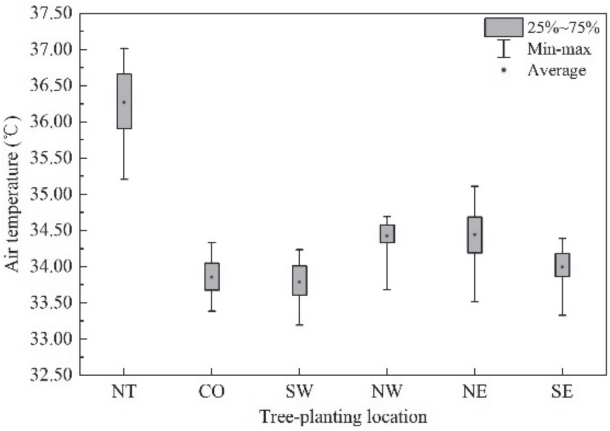

Fig. 10. Numerical boxplot of air temperature at pedestrian height (1.5 m above the ground) of different tree-planting schemes.

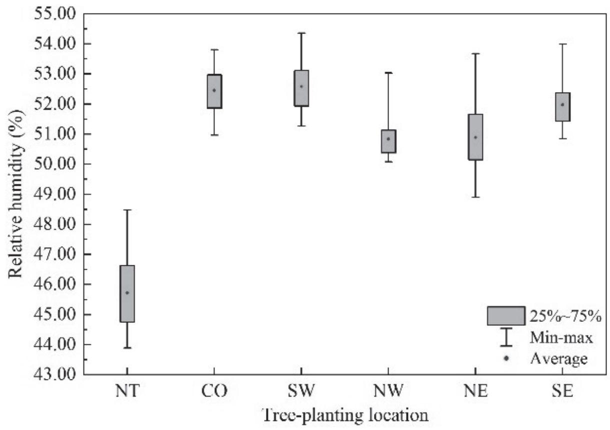

Fig. 12 Numerical boxplot of relative humidity at pedestrian height (1.5 m above the ground) of different tree-planting schemes.

temperature values (i.e., the air temperature in most areas). As seen from the figure, the trees have a cooling effect on the whole site. The air temperature in most areas of the SW, CO and SE schemes was lower than that of the other three schemes, and 25%-75% of the temperature values were between 33.61ºC and 34.18ºC, while the temperature values of 25%-75% of the other two schemes were all higher than 34.18ºC. Among them, the SW scheme can reduce the air temperature of the site to 33.19ºC, which was 2.01ºC lower than the lowest temperature of the site without trees.

In conclusion, the planting of trees can not only affect the solar radiation heat transfer but also change the air flow and local heat transfer, therefore affecting the temperature distribution at the site. From the perspective of air temperature at the site, it is suggested to plant trees in the southwest or middle of the site, where the overall temperature at the site is the lowest and the degree of cooling is the highest. Different planting locations of trees can form different activity spaces [31]. The trees in the above two schemes are planted at the edges and the centre of the site, which can be selected according to the actual needs of the site space design. The chairs and tree pools are set under the trees to form a relatively comfortable outdoor activity space for staying.

Impact of Tree-Planting Location on the Distribution Characteristics of Relative Humidity at the Site

Compared with the NT scheme, the other five schemes have higher relative humidity (Fig. 11). In addition, except that the highest relative humidity of the SE scheme is located west of the tree, the highest relative humidity of the site was located under the tree, and the transpiration of plants increases the absolute water content in the air. Additionally, the area under the tree was cooler, and the percentage of water molecules in the air increases, so the relative humidity was higher there. The relative humidity of the SW scheme was up to 54.36%, which was 5.88% higher than that of the scheme without trees.

According to the numerical boxplot of relative humidity (Fig. 12), compared with the NT scheme, the planting of trees improved the overall relative humidity of the site. Under the influence of different planting locations, the characteristics of humidity distribution in the field were significantly different. The areas with higher humidity are in the southwest (CO, SW), northwest (NW), northeast (NE) and south (SE). In addition, the relative humidity values of the 25%~75% area of the SW and CO schemes were significantly

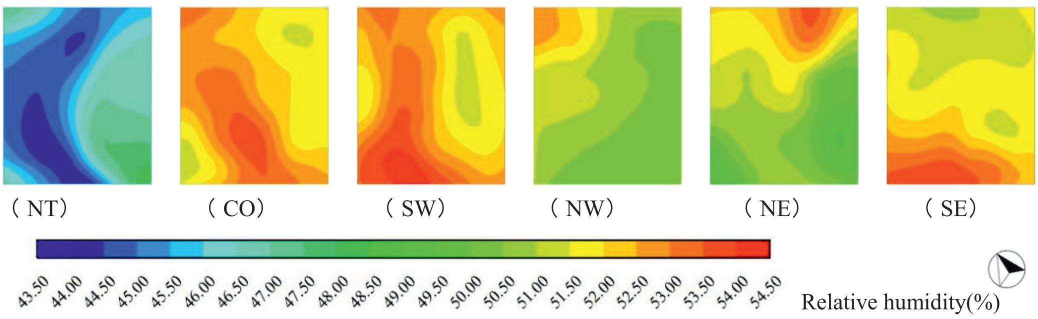

Fig. 11. Relative humidity distribution at pedestrian height (1.5 m above the ground) of different tree-planting schemes.

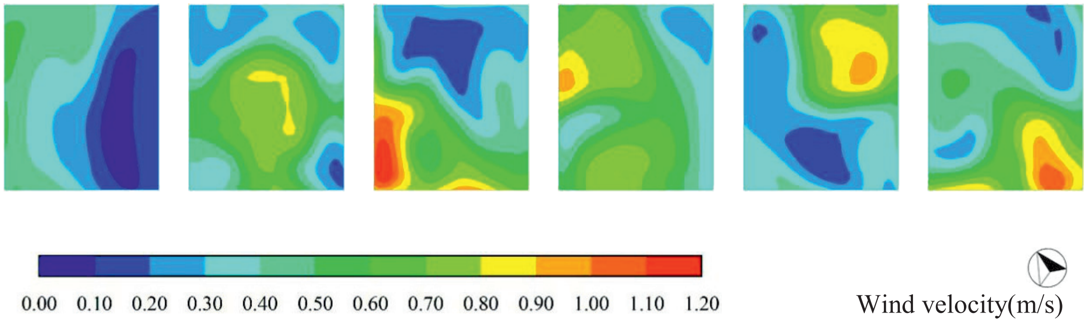

Fig. 13. Wind speed distribution at pedestrian height (1.5 m above the ground) of different tree-planting schemes.

higher than those of the other three schemes, with the relative humidity reaching 51.93%~53.11% and 51.86%~52.97%, respectively. The relative humidity in the middle and west sides of the centre of the site was higher than that on the east side of the site. By comparing the distribution of site temperature and site humidity (Fig. 9, Fig. 12), it was found that the distribution characteristics of site temperature and humidity are relatively similar, and the relative moisture content of air was different under different temperature conditions. Therefore, the relative humidity mainly depends on the temperature. In summary, transpiration of trees plays an important role in the increase in relative humidity at 1.5 m at the site, especially at calm wind sites with low temperature and relatively high relative humidity.

Impact of Tree-Planting Location on Wind Speed and Relative Humidity at the Site

Fig. 13 shows the wind speed distribution at a height of 1.5 m at the site. Combined with the wind direction distribution diagram (Fig. 9), compared with the NT scheme, the planting of trees completely changed the wind speed distribution at the pedestrian height of the site and significantly increased the wind speed in local areas (Fig. 14). The maximum wind speed was located under the trees in the five planting locations.

In terms of the maximum wind speed at the site, the maximum wind speed of the SW scheme was 1.20 m/s (Fig. 13). This is due to the shading and transpiration of plants; the air temperature in the southwest corner of the site decreases, and the thermal difference in the southeast side of the site increases. Additionally, the “narrow pipe effect” caused by the narrow alley accelerates the flow of wind speed. The air flow formed by the thermal difference and the air flow formed by the external air flow were in the same direction, and the two effects were superimposed, so the wind speed there was the highest.

In summary, trees can have a greater impact on the wind speed in the micro space. In the case of poor ventilation conditions, a single tree can accelerate the airflow and improve the local ventilation, especially by significantly increasing the wind speed in the area under the trees. When the trees were planted in the windward direction of the incoming wind of the site, the external wind and the internal wind can form a high wind speed area under the trees.

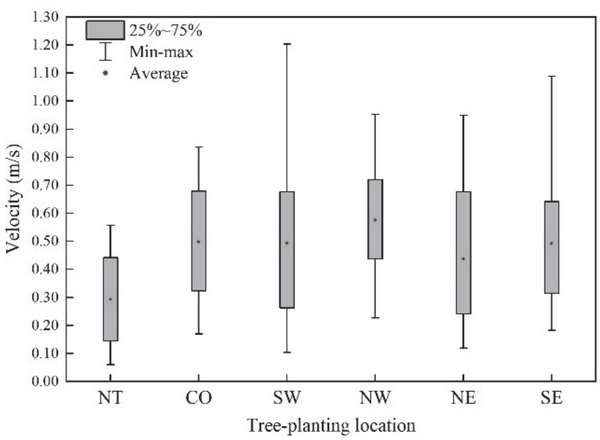

Fig. 14. Numerical boxplot of wind speed at pedestrian height (1.5 m above the ground) of different tree-planting schemes.

The Impact of Tree-Planting Location on Thermal Comfort at the Site

It can be seen from the figure that different tree-planting locations lead to great differences in thermal comfort distribution at the height of 1.5 m of the six schemes (Figure 15). In general, the thermal comfort at the site of the NT scheme was the worst, especially on the west side of the site, with the highest UTCI reaching 38.17ºC. According to the UTCI rating table [44], it has reached the level of “very intense stress”. The distribution of thermal comfort in the other five schemes depends on the tree-planting location. Except in the SE scheme, in which the lowest UTCI value is slightly to the west under the tree, and in the CO scheme, in which the lowest UTCI value is to the south under the tree, the lowest UTCI values of the other three planting schemes are under the tree. Whether it is the site with or without trees, the comfort distribution of the six schemes is greatly related to the air temperature and relative humidity, and the places with low air temperature

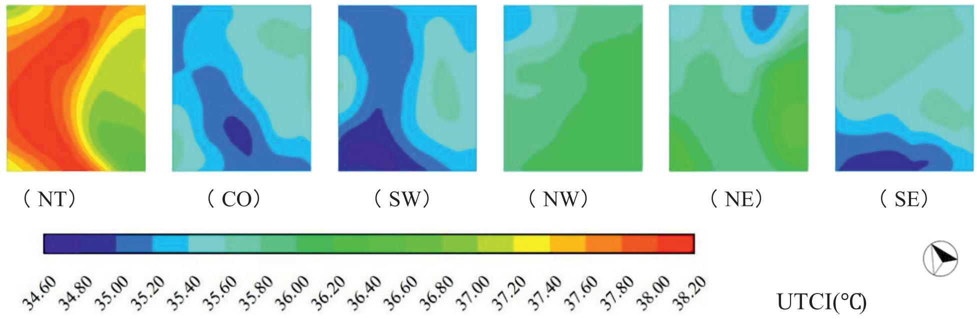

Fig. 15. UTCI distribution at pedestrian height (1.5 m above the ground) of different tree-planting schemes.

and high relative humidity were more comfortable. It can be seen that at a site with a low wind speed, a small change in wind speed has little effect on the improvement of thermal comfort.

Combined with the UTCI rating table [44], it can be seen from Figure 16 that the UTCI values of the 6 schemes, except that the UTCI value of only a small part of the NT is in the "very intense stress" state, and the UTCI values of the other five schemes are all in the "very intense stress" state. The average values at a height of 1.5 m of the 6 schemes in sequence from small to large are SW<CO<SE<NE<NW<NT.

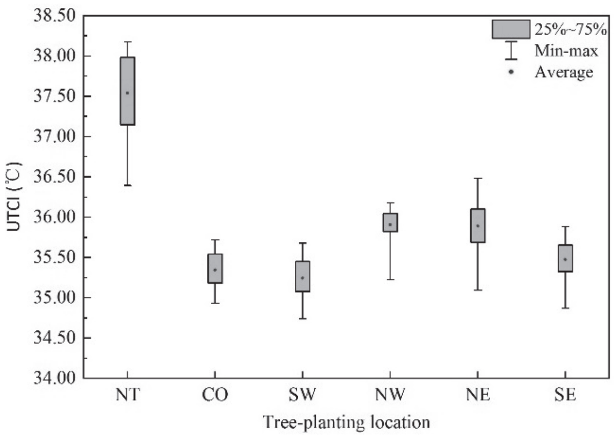

Fig. 16. Numerical boxplot of UTCI at pedestrian height (1.5 m above the ground) of different tree-planting schemes.

The planting of trees reduces the overall UTCI value of the site and has obvious cooling benefits to the site, which improves the comfort at the site. Compared with the NT scheme, the SW scheme reduces the average, maximum, and minimum UTCI values at a height of 1.5 m the most, with decreasing values of 2.29ºC, 2.49ºC, and 1.66ºC, respectively. From the 25% to 75% UTCI value at the site, the overall value of the SW scheme was small, followed by the CO scheme, which was similar. The NW and NE schemes have higher overall values and poor thermal comfort.

ΔUTCI was used to characterize the difference between the UTCI of the five tree-planting schemes and the NT scheme (Fig. 17) to eliminate the interference of buildings and other factors. It can be seen from the figure that the cooling effect in the middle and west of the middle of the site is better than that of the east in these five planting locations. The best cooling effects of the CO, SW and SE schemes were located near the southwest corner. From the cloud diagram of the NT scheme in Fig. 17, it can be seen that the comfort level is the worst here, and the improvement effect of planting trees was the most obvious. For the NW and NE schemes, the comfort on the north side of the site was best improved. It can be seen that the comfort of trees near the trees was much improved. In addition, the planting location of the arbor also affects the improvement of the thermal comfort of the site: the trees closer to the incoming wind are better than the trees farther away from the incoming wind.

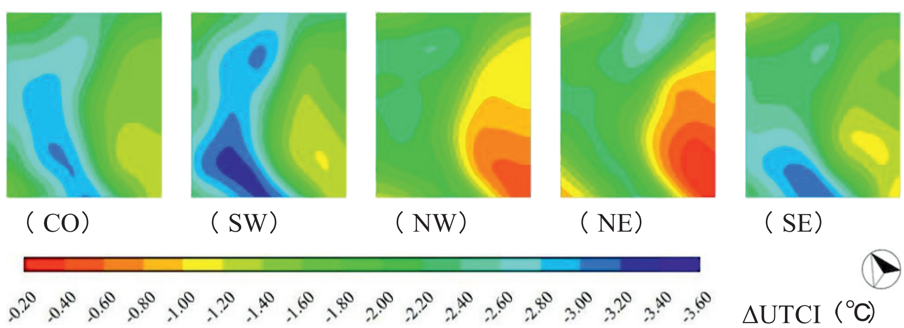

Fig. 17. ΔUTCI distribution at pedestrian height (1.5 m above the ground) of 6 different tree-planting schemes.

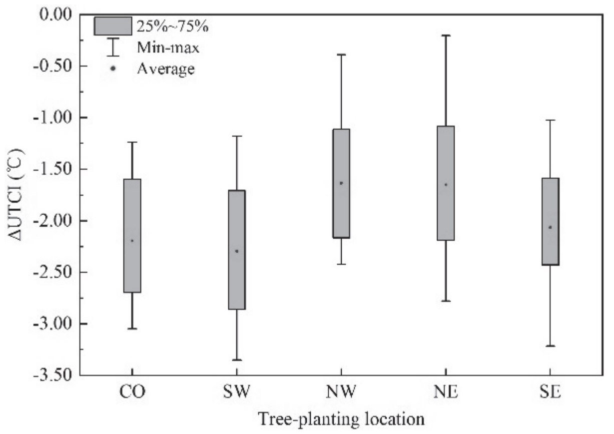

Fig. 18. Numerical boxplot of ΔUTCI at pedestrian height (1.5 m above the ground) of 6 tree-planting locations.

Fig. 18 shows the difference in ΔUTCI, and the negative number indicated the cooling effect of trees on the site. It can be seen from the figure that the five planting locations have a certain degree of cooling effect on the whole site. The average cooling effect of different schemes is between 1.63ºC and 2.30ºC, and the SW scheme has the best cooling effect. In terms of the overall cooling effect, the SW scheme has the largest cooling benefit in most areas. The maximum cooling effect appeared in the SW scheme, which reached 3.35ºC, followed by SE and CO, which were 3.21ºC and 3.05ºC, respectively. The worst was the NW model, but the cooling effect on the site can reach 2.42ºC. The minimum value of the cooling effect was 0.20ºC in the NE scheme. The average, maximum and minimum values of the cooling effect of trees planted in different locations were quite different. This was because the temperature of the site in the NT scheme was higher and the wind speed is basically calm. Therefore, after planting, trees are equivalent to a "cold source" with obvious effects. The pressure difference between the space at a height of 1.5 m below the trees and the surrounding area was large to form convection. However, due to different planting locations of trees, the location of the "cold source" was different, leading to changes in the location and size of the convection. Therefore, the cooling effect of several tree-planting patterns was not the same. From the perspective of the impact of tree-planting location on thermal comfort, tree-planting on the southwest side of the site has the best effect on improving thermal comfort, followed by the middle and southeast corners.

Discussion

In actual project construction, the formation of such micro space is constantly formed in the process of urban renewal, so it will not be too ideal in shape, location and orientation. Therefore, the conclusion according to the article suggested that in the future micro space design, trees be planted in southwest slant on the west side of the site as far as possible, and a more private space can be set under the trees to make people feel safe and do some activities such as having afternoon tea and rest. Trees can also be planted in the centre of the site. At this time, a relatively open space can be set in the centre of the site, where users can carry out more interactive activities, such as chess, cards, talking, and walking. If the actual site does not allow trees to be planted in the southwest side and in the centre, it is considered to plant trees in the south or southeast side. At this time, it is suggested to set more activity sites in the south side of the site.

In this study, although there was only one tree in the small open-public space in the old community, its green coverage rate reached 30% compared with the site size. The average temperature at the site can be reduced by 1.83-2.43ºC by comparison among the trees in different planting locations and the pavement without trees. The area with the largest cooling range was located under the tree in the SW scheme, which can reach 3.67ºC. This fits with the conclusion of Errell's findings that trees can cool down to 3ºC or even more when wind speeds are low [45]. Additionally, some researchers measured the points under shade and the points without shade and found that the temperature difference can also reach 3ºC [46]. In addition to the low wind speed, most buildings at the site are lower than the plants. Trees exposed to solar radiation can not only cool the surroundings through transpiration but also block the solar radiation into the site through the shading effect. The combined effect of the two makes the temperature drop more [47]. Edward's research also confirmed the idea that the same plants have better cooling effects in lower buildings than in higher buildings [18].

The trees planted in the site have a cooling effect on the whole site. Additionally, the temperature distribution at the site is determined by the layout of the trees. The low temperature zone in the site is all located under the trees, which is different from the experimental conclusion obtained by Li et al. by changing the layout of the trees in the yard [31]. Analysis of the causes of the two found that the environmental conditions are different; the wind speed of the field is different. Manickathan's experiments can explain this phenomenon. The cooling effect of plants on the environment is affected by wind speed. When wind speed is high, trees extract sensible heat flux from a larger space and generate convection, thus extending the influence range of trees. However, when the wind speed is low, the latent heat cooling energy of trees is not easy to flow, so it can have a greater cooling benefit for the local area around the trees [48]. Both Dimoudi and Errell have shown that increased wind speed reduces the local cooling benefits of plants [45, 49]. Therefore, in this kind of hot and humid area with high building density and low wind speed, tree planting plays a more obvious role in the increase in wind speed. In this study, tree planting increased the average wind speed at the site. Under low wind speed, the local trees have a stronger cooling effect, which makes the pressure difference between the space under the trees and the surroundings increase and thus can play a role in improving the wind speed. Additionally, although both of them were located in the site with buildings all around, there was only one opening for wind at Li's research site, and vortices are generated at the site where trees are planted to reduce the wind speed [31]. In this study, there were alleys in the surrounding buildings, and the wind generated in the alleys and at the site can also form convection, affecting the wind speed at the site.

This study focused on the impact of the planting location of trees on the microclimate and thermal comfort. Because the experimental study needs to control variables, only one common tree species in Huizhou was selected for the study under a common condition. In future experiments, different tree species can be discussed, and the changes in the physiological characteristics of trees themselves, such as crown height, crown width, leaf area index (LAI) and other factors, have an impact on microclimate and thermal comfort, which can provide guidance for the selection and planting of trees at different sites. Due to the change in the solar elevation angle, the shading effect of trees on the site is different at different times, and the impact on the site environment is different. This study only discusses how to better improve the site environment and enhance the thermal comfort of the human body at 2:00 p.m. in summer. The conclusion can provide suggestions for the spatial location selection of activities in the summer afternoon, such as afternoon rest and afternoon tea. In future research, we can also discuss the influence of trees in the morning, evening and night on the site to combine the results of the day to better guide the practical application.

Conclusions

In this study, PHOENICS software was used to simulate the effects of different tree-planting locations on the microclimate and human thermal comfort of the old urban micro space. Through the analysis of the results, the following conclusions are drawn:

(1) In terms of microclimate, planting a tree in micro space can significantly lower the temperature, increase the humidity, and improve the ventilation and thermal comfort at 2:00 p.m. at the pedestrian height (1.5 m above the ground). The planting of trees in the southwest has the best cooling and humidifying effect on the courtyard in the afternoon, followed by the planting in the centre of the site and southeast, and the planting in the northeast and northwest has poor cooling and humidifying effects.

(2) In a poorly ventilated micro space, a tree can improve ventilation, especially when they were planted in the upwind direction of a site with low temperature.

(3) Among the five tree-planting schemes, the average, maximum and minimum UTCI values of tree planting in the southwest of the micro space and the UTCI values of most areas in the site were all the smallest, which means that tees planned in the southwest of the micro space had the best cooling benefits.

(4) From the perspective of microclimate and thermal comfort improvement, it was suggested to increase the tree planting space as much as possible in the urban micro space reconstruction, and plant trees in the southwest side of the space can achieve better cooling and thermal comfort improvement effects. It was suggested to set the activity space under the tree, where the space is the most comfortable. Second, it can also be selected in the middle and southeast according to the actual situation. The effect of cooling and thermal comfort improvement is relatively good.

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Conflict of Interest

The authors declare no conflicts of interest.

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