Effects of different vertical façade greenery systems on pedestrian thermal comfort in deep street canyons

Abstract

Vertical greenery systems (VGSs) have been adopted in city planning operations to mitigate excess heat in hot and humid subtropical cities. This study focused on the influence of different arrangements of vertical greening on pedestrian thermal comfort and particulate matter with a diameter of 10 μm (*PM10*) in street canyons. In this paper, the ENVI-met computational fluid dynamics (CFD) method was used to investigate the effects of different façade greenery arrangements with the same amount of greenery in the Nan Hai Yi Ku (NHYK) industrial district. On-site measurements were used to validate the simulation results in a transition season. The results showed that greening façades could improve pedestrians' thermal comfort with physiological equivalent temperature (*PET*) value reductions varying from 0.17 ◦C to 1.4 ◦C. Under a certain amount of greenery, the critical factor determining pedestrians' thermal comfort was the coverage rate of the greening façade near the pedestrian level. Specifically, increasing the greening façade coverage near the lower parts of street canyons could enhance the pedestrian-level cooling effect. In addition, the VGSs positively affected the pedestrian-level air quality in the street canyons. Nevertheless, the changes in pedestrian-level *PM10* concentration induced by the presence of VGSs were not very obvious under the building-parallel wind direction.

Keywords: Outdoor thermal comfort; ENVI-met; Vertical greenery; Greenery arrangement; PET; Air quality

1. Introduction

The rapid development of urbanization leads to an increase in impervious building blocks,and this process can influence the outdoor thermal comfort and alter the evaporation and energy balance processes that occur between the land surface and ambient temperature conditions (Fitria et al., 2019; Morakinyo et al., 2019). Increasing heat stress and deteriorating urban heat island (UHI) conditions urge us to adopt mitigation measures to cope with these pressing issues. Previous studies have confirmed that the thermal sensation is superior in areas with higher vegetation cover than in areas with lower vegetation cover (Safikhani et al., 2014; Salmond et al., 2016). A recently published study concluded that greening is an effective microclimate mitigation strategy, especially in urban areas (Ch`afer et al., 2021). For example, through scaled outdoor field measurements, Chen et al. (2021) found that double-row trees produce better cooling effect than single-row trees in the pedestrian level of the street, and species with big crown have better cooling effect than small one during the day. Li et al. (2022) showed that a campus with surrounding vegetation has a good outdoor thermal environment, and the shading and transpiration effects of tall trees help keep the temperature stable throughout the day, with a temperature difference within 2 ℃. It has also been proposed and verified that increasing urban vegetation can help improve urban microclimate and human thermal comfort, and reduce the urban heat island effect (Coutts et al., 2015; Yang et al., 2011). However, in high-density cities such as Shenzhen, the land area, and thus the tree-planting ability, is often limited (Morakinyo et al., 2019). Notably, the surface area of a building is much larger than the surface area of the ground and roof of the building, thus providing multiple planting platforms for greening.Compared with other greening methods, vertical greening systems (VGSs) can provide passive cooling for indoor and outdoor areas without occupying valuable land resources and while preventing the absorption of solar radiation, thereby reducing the UHI effect (Yang et al., 2018). A VGS is a practical measure with which the thermal environments of high-density cities can be improved. In addition, VGSs psychologically impact urban residents due to their aesthetic appearance (K¨ohler, 2008; Wong et al., 2010; Jungels et al., 2013) and induce economic benefit through energy savings and construction material durability (Joye et al., 2010; P´erez et al., 2014).

Previous studies have shown that VGSs can effectively improve their immediate surrounding microclimates (Coma et al., 2017; Medl et al., 2017; Besir and Erdem, 2018). Acero et al. (2019) found that VGSs mainly provide thermal benefits for pedestrians located near the bottom of the façades. When greenery is placed above 6 m on a façade, it markedly reduces the effect on the pedestrian level. VGSs can reduce the temperature of the exterior surfaces of buildings by shielding direct solar radiation. VGSs also affect building energy consumption because they can increase the latent heat flux and decrease the sensible heat flux, thus changing the energy balance on the building surface (Peng et al., 2020). More specifically, the improvement of outdoor thermal comfort, the mitigation of UHIs, and the reduction in building energy are advantages of VGSs (P´erez et al., 2014; Safikhani et al., 2014; Coma et al., 2020). In a hot-arid climate, Holm (1989) found that using VGSs on a west-facing building façade can reduce the indoor temperature by 1–4 ◦C. Wong et al. (2010) investigated the influence of façade greening coverage on air temperature (Ta) levels and found a maximum Ta reduction of 1 ◦C and an average reduction of 0.3 ◦C with 100% façade greening coverage. Ng et al. (2012) used the ENVI-met approach to discuss the potential cooling effect of façade greening in Hong Kong; their results showed that if 30–50% of a façade is covered with greenery, the Ta can be reduced by 1 ◦C during the daytime and nighttime. Based on these advantages, VGSs are now widely used in building design to reduce the urban energy consumption, improve the thermal environment and compensate for the lost green space，and have thus become a common practice in many cities (Peng et al., 2020; Xue et al., 2017). In large Chinese cities, such as Beijing and Shenzhen, VGSs have been adopted in the building design field by issuing incentive packages and design guidelines. Although many studies have investigated the cooling effects of VGSs in urban environments (Kontoleon and Eumorfopoulou, 2010; Morakinyo et al., 2019; Peng et al., 2020), few have quantitatively studied the thermal improvements induced by different greenery arrangements. Therefore, this research aims to quantitatively study the influence of different VGS arrangements on the outdoor thermal comfort in subtropical regions.

In addition, urban greenery plays a vital role in the dispersion of atmospheric particulate matter in streets. Many studies have shown that plant leaves can capture particulate matter (PM) and reduce ambient concentrations (Li et al., 2019; Shao et al., 2019; Vera et al., 2021). For example, Pugh et al. (2012) demonstrated that increasing deposition by planting vegetation in street canyons may reduce street-level concentrations by 60% for PM. Chen et al. (2015) and Eisenman et al. (2019) found that urban trees, shrubs and grass can improve footpath air quality to a certain degree (7–15%) and are related to street canyon aspect ratio. In addition, plant heights also have different effects on the diffusion of pollutant concentrations in street canyons. Low-level hedges have been shown to typically reduce pollutant levels along sidewalks (Gromke et al., 2016). However, high-level street trees alter the local wind field, attenuate circulating vortices within street canyons, reduce the rate of air exchange at the top of street canyon buildings, diminish the street canyon ventilation effect, and increase the concentrations of atmospheric pollutants (Ng et al., 2012; Tong et al., 2015; Yang et al., 2020; Hu and Ma, 2021). Compared to traditional trees used to green streets, VGSs may have a smaller impact on the street wind speed and may prevent these adverse effects on street air quality (Ysebaert et al., 2021; Tomson et al., 2021a, 2021b). Although the impact of vegetation on air quality at pedestrian level in street canyons has received extensive attention, few studies have evaluated the combined effects of vertical greening on microclimate and air quality in street canyons. Even though there are some numerical simulation studies focusing on both aspects (Rui et al., 2018; Krüger et al., 2011), the main research content is the urban geometry or residential area, not the street canyon. Consequently, this study further simulated and analyzed the effect of vertical greening on PM10, in order to understand the role of the VGS in the coupled effect of air quality and microclimate, so as to identify vertical greening features with comprehensive ecological benefits.

To study and investigate the effects of different greening arrangements in deep street canyons on the thermal comfort at the pedestrian level and to further explore the impact of vertical greenery on PM10, we used the Nan Hai Yi Ku (NHYK) industrial area in Shenzhen, China, as an example (see Section 2). In this paper, we used ENVI-met to perform the simulations. To ensure a high modelling accuracy, we conducted on-site measurements before the model validation (see Section 2) and finally analysed the Ta, physiological equivalent temperature (PET), mean radiant temperature (MRT), and PM10 concentration values derived based on the simulation results (see Section 3).

2. Methodology

2.1. Study area

Shenzhen is a high-density mega-city located along the coastline of Southeast China (22◦4′ N, 114◦0′ E), with a total area of 1996.8 km2 and a population of 13.0 million people (http://www.sz.gov.cn/). Shenzhen has hot summers and warm winters and is classified as having a subtropical maritime climate. Throughout most of the year, the weather is characterized by high temperatures (23 ◦C), high relative humidity and significant precipitation of 1933.3 mm (http://weather.sz.gov.cn/). These climate conditions lead to extremely hot and irritating summers; thus, mitigating intolerable summertime outdoor thermal comfort levels is a vital issue for ensuring environmentally friendly urban design in Shenzhen.

The study area is located in the NHYK district, which contains an office building converted from six old factory buildings; commercial buildings are located on the east side of the foundation, while high-rise residential buildings surround the rest of the structure (Fig. 1(a)). The office building envelope has a long history and poor thermal insulation performance. Therefore, it is necessary to combine façades greening with the envelope structure to reduce energy consumption and improve thermal comfort. The total studied area is 300 m × 300 m. The façades of the six main buildings within the analysed block are covered with VGSs, and all vertical vegetation is planted 0.5 m from the exterior concrete walls.

2.2. On-site measurements

The on-site measurements were carried out on a typical hot day in summer (10 July 2019) and lasted for 8 h (9:00–17:00). The meteorological conditions were monitored using a Japan Tobacco-Indoor Air Quality (JT-IAQ-50) weather station set in the geometric centre of the transverse inner street (Fig. 1(d)). All instruments were placed 1.5 m away from the building façade at the pedestrian level (1.5 m above the ground; see Fig. 1(b)), and the data were logged at 1 min intervals. The meteorological parameters included the air temperature, relative humidity, black-ball temperature, wind speed and wind direction. The measurement instruments are shown in Fig. 2, and detailed information on the utilized instruments is listed in Table 1.

2.3. Validation of ENVI-met

To simulate and assess the impacts of greening arrangements on the outdoor thermal environment and air pollution, the ENVI-met V4.4 model (Bruse and Fleer, 1998) was used to simulate the Ta, MRT, PET, and PM10 values. The MRT was estimated according to the following expression (ISO7726) (Eq. (1)) in Envi-met:

$$MRT = [T_{globe} + 273.15)^4 + (Tglodbe - Tair) \cdot (1.1 \cdot 10^8 \cdot WS^{0.6}) /(\varepsilon \cdot D^{0.4})]^{0.25} - 273.15 \qquad (1)$$

where ε and D represent the emissivity of the globe-thermometer and itsdiameter (mm), T_{globe} denotes the globe temperature (◦C), Tair is the air temperature (◦C), and WS is the wind velocity (m/s).

Here, PET is used to evaluate the outdoor thermal comfort. PET is based on the Munich Energy-balance Model for Individuals (MEMI), which models the thermal conditions of the human body in a physiologically relevant way (H¨oppe, 1999). The standard human metabolic rate and other human parameters are often used to calculate PET by considering the effects of key meteorological parameters, activity, clothing, and individual parameters on comfort. The human parameters utilized in this paper were set as follows: the metabolic rate was set to 164.49 W, the clothing thermal resistance was 0.5, the height was 1.75 m, and the weight was 75 kg, corresponding to a 35-year-old adult male.

2.3.1. Description of the ENVI-met model

ENVI-met is a microenvironmental numerical simulation software developed by Professor Bruce and his team in 1998 based on 3D nonhydrostatic and thermodynamic models. The modelling software enables dynamic microenvironmental conditions to be obtained by simulating building-vegetation-air-soil interactions at small and medium scales in cities. ENVI-met is mainly composed of a threedimensional main model, a one-dimensional boundary model and a nested grid. The three-dimensional model mainly includes building, vegetation, atmospheric and soil models, as well as nested grids outside the main model; this setup aims to reduce the impact of the surrounding environment on the simulation results, thereby improving the simulation accuracy (Bruse and Fleer, 1998). Currently, ENVI-met is mostly used to simulate urban thermal environments, urban wind environments, and air pollutant distributions. More complex model systems and physical principles have been introduced in detail in the references and on the ENVI-met website (http://www.envi-met.com/; Sebastian, 2012).

In this study, we focused on the thermal impacts of different vertical greening arrangements and discussed the effects of VGSs on pollutant concentrations. In ENVI-met, the appearance and physical characteristics (shape and height) of the analysed vegetation are usually parameterized using the leaf area density (LAD) and leaf area index, and the heat, moisture and momentum exchanges are considered when simulating the effects of vegetation on atmospheric transport (Morakinyo et al., 2016). ENVI-met V4.4 allows time-of-day climate variables to be input, so the default façade greening module in the software was used to construct diversified VGS layouts, and the other relevant parameters were input according to the measured data.

ENVI-met V4.4 allows the meteorological boundary conditions of Ta and RH to be updated during the diurnal simulation process, while the wind speed, wind direction and cloudiness remain unchanged. Therefore, the hourly Ta and RH data collected on the measurement day were forced at the model boundary using a ’forcing manager’ to initialize the model. On the day of initialization, the wind speed at 10 m above the ground was set to 2 m/s, and the wind direction was east (90◦),representing typical summer wind conditions in Shenzhen. The albedo of the building walls, roofs and roads was set to 0.3 (Ouyang et al., 2020; Morakinyo et al., 2019, 2017; Ng et al., 2012), and the initial soil temperature was set to the ENVI-met V4.4 default value of 19.85 ◦C. The average Ta and RH values collected from 9:00–17:00 during the actual measurement collection were selected for a correlation analysis with the average values reflected in the time-by-time results of the validation simulation (the monitoring points are shown in Fig. 1).

2.3.2. Numerical setup

The geometric information of the analysed building and streets, including their layouts and dimensions, was obtained from the Shenzhen Planning Department for the validation of the ENVI-met model. Notably, nonessential building and road details were omitted or simplified to develop a generic computational model. In particular, the building geometry was simulated as aggregates of blocks. The heights of the building ranged from 18 m to 20 m, and the building material characteristics are listed in Table2 (all building materials were concrete slabs). The unvegetated ground surfaces were covered with concrete roads and traditional asphalt roads. ENVI-met has a typical gridded spatial resolution of 0.5–10 m and a spatial resolution of 10 s. In this paper, a 3 m × 3 m × 3 m horizontal and vertical resolution was selected to increase the simulation accuracy. The computational model domain covered a horizontal area of 300 m × 300 m (i.e., 150 × 150 grid cells) and a vertical height of 90 m (i.e., 30 grid cells). The building (Fig. 1) was rotated 35◦ clockwise to facilitate the visualization of the layout and greenery simulations on the building façade.

Regarding greenery, the total leaf area, spacing, height and width of the vertical vegetation in the target area were measured before the simulations and were reproduced in the computational domain. These parameters remain the same throughout the rest of the paper (see Fig. 3 and Table 2).

For the pollutant dispersion simulations, the species, source geometry, and background level (Table 2) were used to calculate the emission rate in ENVI-met V4.4. The initial condition parameter calculations included the traffic flow, composition, and emission factor distributions for the given traffic scenario per vehicle class. Regarding the traffic flow distribution, the peak morning and evening hours in Shenzhen were similar to the inner-urban road traffic distribution provided by the software The Daily Traffic Value (vehicles/24 h) in the NHYK street canyons was determined according to the historical data in which approximately 4224 vehicles were counted on Liu Xin Fourth Street Road in Shenzhen. There are two lanes in this street segment, and the number of vehicles per hour was thus automatically generated. The light duty vehicles (LDV/transporters), urban bus (public transport), and PC (passenger car) proportions in the overall traffic composition were 1%, 6% and 93%, respectively. The information comes from the basic data of Liu Xian Dong Headquarters Base provided by Shenzhen Planning and Land Development Research Center.

Regarding the emission factors derived for the given traffic scenario per vehicle class module, NO/NO2 was generating using the default value, and the proportion of PM2.5 in the PM10 value was found to be 0.64. Finally, the automatic calculation results are shown in Fig. 4.

2.3.3. Validation results

Table 3 shows the main statistics on the model accuracy: Pearson's coefficient of determination (R2), Root Mean Square Error (RMSE) and mean absolute percentage error (MAPE). In general, the closer R2 is to 1, the closer the RMSE and MAPE are to 1 the reliability increases (Di Giuseppe et al., 2021). According to previous studies, Ta and RH can be well estimated. R^2 = 0.79–0.96 and R^2 = 0.77–0.85 (Morakinyo et al., 2017; Tong et al., 2016; Berardi, 2016; An et al., 2015; Srivanit and Hokao, 2013; Lilliana et al., 2013; Müller, Kuttler et al., 2013), RMSE= 0.46–4.04 ℃ and RMSE = 1.62% - 19.0% (Di Giuseppe et al., 2021; Forouzandeh, 2018; Duarte et al., 2015), MAPE value is less than 10% (Cruz et al., 2021; Chang et al., 2019). Furthermore, many previous studies have also verified the accuracy of the software (Tan et al., 2016; Ng et al., 2012). These studies also tested and found reasonable consistency between ENVI-met modeling and observed microclimate conditions that can be adapted to urban environments in multiple countries (Di Giuseppe et al., 2021).

The correlations between the Ta and RH values recorded on the actual measurement day and obtained in the simulation results were strong (as shown in Fig. 5). R^2 values equal to 0.76 for Ta and 0.91 for RH; RMSE values equal to 0.7 ◦C for Ta and 15.4% for RH; MAPE values equal to 0.6% for Ta and 17.9% for RH. The R2 and RMSE values indicate a strong agreement between simulated and measured Ta and RH. These results show that the measured and simulated values were strongly correlated and that the software simulation accuracy meets the requirements.

2.4. Case description

In this paper, six case studies were set up to analyse the effects of different VGS arrangements on the outdoor thermal comfort of street canyons (see Fig. 6**)**. First, the primary case with no VGS is studied (case 1); then, five different VGS arrangement cases are considered (cases 2–6). The total leaf area in each case remained the same except in the primary case, but the vertical green coverage rate within 6 m of the ground differed among cases. In this study, the coverage of greening façades at the pedestrian level was calculated at a height of 1.5 m; in the simulations, the coverage of greening façades near the pedestrian level was calculated at a 6 m height because the height of the simulated building was 18 m and the grid resolution in the vertical direction was 3 m. In case 2, the vertical greening distribution was set to characterize vertical strips, while in case 3, the vertical greening distribution was set to represent horizontal stripes. In case 4 and case 5, the vertical greenery covered only the lower and upper parts, respectively, of the façade. In case 6, the vertical greening was distributed in a staggered pattern on the building wall to simulate the mosaic façade beautification strategy.

3. Results and discussion

In this section, the pedestrian-level thermal impacts of VGSs are presented. For the various VGS arrangements considered herein, the effect of greening coverage on the outdoor temperature is discussed.

3.1. Effect of greening coverage on outdoor temperature

Human thermal comfort is defined as "the state of mind that expresses satisfaction with the surrounding environment" (RAA-C, 2013). Such biometeorological factors are mainly influenced by conditions such as the air temperature, radiant temperature, wind velocity, humidity, clothing, and metabolic rate production (Ibrahim et al., 2021). This study used *Ta*, *MRT*, and an indicator specifically used for outdoor comfort evaluations—*PET*—to evaluate the influence of greening coverage on the outdoor temperature.

3.1.1. Air temperature

To quantitatively assess the effects of greening coverage at the pedestrian level, the temperature difference between each case with greening coverage and the case with no greening coverage was defined as follows: $\Delta Ta = Ta_{case\ 1} - Ta_{case,\ i}$ (2)

where i = 2, 3, 4, 5 or 6, referring to the cases listed in Fig. 6; $Tacase1$ refers to the corresponding specific Ta value among the values derived for different façade greening cases, and $Tacase,i$ denotes the Ta value derived for the primary case (no greening coverage).

According to the analysis of the weather station data, the highest temperature in summer appears in the study area at 14:00. In this sense, the ΔTa (air temperature reduction) distributions indicated by pedestrians in different cases at a height of 1.5 m at 14:00 are shown in Fig. 7. The overall maximum Ta reduction was 0.28 ◦C, obtained due to the presence of greening coverage in case 4. Case 4 also provided the maximum area-averaged reduction in Ta (0.18 ◦C) among all the analysed cases. In case 3, the maximum and area-averaged reductions in the Ta values were 0.19 ◦C and 0.11 ◦C, respectively. The pedestrian-level cooling effect was not as practical in case 3 as in case 4 because the pedestrian-level vertical greening simulated in case 3 was half of that simulated in case 4. For the two other cases (case 2 and case 6), the Ta reductions were the same, as the same pedestrian-level greening coverage (50%)

was applied in both cases. Overall, among all the investigated cases, the cooling effect induced by the case 5 greening scheme was the worst.

Fig. 8 shows the ΔTa vertical distributions in the street at 14:00 forall cases. The results derived for all cases show that the street canyon cooling effects induced by vertical greening decreased with the vertical height. Case 3 and case 4 had similar reduction patterns, and case 2 and case 6 also had similar reduction patterns. More specifically, cases 3 and 4 had better cooling effects along the vertical plane among all the cases, whereas case 5 has the worst cooling effect among all the cases. This suggests that the case 3 and case 4 schemes should be adopted in architectural design under similar weather conditions as those in the study area, while case 5 should be avoided.

3.1.2. Mean radiant temperature

Similar to the previous definition, the differences in *MRT* (ΔMRT) between the cases with greening coverage and the case with no greening coverage were defined as follows:

$$\Delta MRT = MRT_{case1} - MRT_{case,\ i} \quad (3)$$

where i = 2, 3, 4, 5 or 6, referring to the cases in Fig. 6; $MRTcase,i$ reflects the *MRT* value derived for each of the different cases; and $MRTcase1$ is the *MRT* value derived for the primary case.

The pedestrian-level ΔMRT distributions derived for all cases are shown in Fig. 9. There is a strong correlation between the pedestrian-level greening coverage and the ΔMRTvalues. The *MRT* reduction magnitudes, including the maximum and area-averaged ΔMRT reduction magnitudes, were almost identical for cases with the same greening coverage at the pedestrian level. For case 2 and case 6, which had similar pedestrian-level greening coverages, the ΔMRT

reduction values were similar to each other. For case 5, the Δ*MRT* reduction values were smallest, as there was no pedestrian-level greening.

Fig. 10 shows the Δ*MRT* vertical distributions in the street at 14:00 derived for all cases. Case 3 and case 4 had similar reduction patterns, and case 2 and case 6 had similar reduction patterns. More specifically, case 3 and case 4 had the best cooling effects along the vertical plane among all the cases, whereas case 5 had the worst cooling effect among all the cases. These results suggest that the greenery schemes represented by cases 3 and 4 should be promoted in architectural design under similar weather conditions as those in the study area, while case 5 should be avoided.

3.1.3. Effect of greening coverage on outdoor thermal comfort

To quantitatively investigate the influence of vertical greening façades on outdoor thermal comfort at the pedestrian level, the *PET* differences were calculated between the cases with greening coverage and the case with no greening coverage as follows:

$$\Delta PET = PET_{case\ 1} - PET_{case,\ i} \tag{4}$$

where i = 2, 3, 4, 5 or 6, referring to the cases shown in Fig. 6; $PET_{case,i}$ is the *PET* value derived for each of the different cases, and *PETcase*1 is the *PET* value derived for the primary case.

Fig. 11 displays the diurnal cycle of the area-averaged *PET* differences (Δ*PET*) in the simulated area. During the daytime, Δ*PET* increased until 14:00 and then decreases until 19:00 (sunset). Moreover, case 3 and case 4 induced similar Δ*PET* variation trends, while case 2 and case 6 also had the same trend. Furthermore, the greening arrangement represented by case 5 had the most negligible mitigation effect on outdoor thermal comfort among all the analysed cases.

Fig. 12 shows the Δ*PET* distributions derived at the pedestrian level at 14:00 in all the cases. Case 4 resulted in the largest *PET* decrease, followed by case 3. The greening arrangements in cases 2 and 6 had similar effects on the *PET* values at the pedestrian level. Similar to the previous results, the greening arrangement represented by case 5 has the most negligible decreasing effect on *PET* among all the cases investigated. Furthermore, among all the studied cases, the maximum and area-averaged *PET* values were as high as 1.4 ◦C and 0.49 ◦C, respectively. The lowest maximum and area-averaged *PET* reduction values were 0.4 ◦C and 0.14 ◦C, respectively.

Fig. 13 shows the Δ***PET*** vertical distributions obtained in the E-W street direction at 14:00 for all cases. In this section, case 3 and case 4 had similar reduction patterns, while case 2 and case 6 also had similar reduction patterns. More specifically, case 3 and case 4 had the best cooling effects along the vertical plane among all the cases, with a maximum Δ***PET*** of 0.8 ◦C. Case 5 had the worst cooling effect among all the cases. These results suggest that the greenery schemes represented by cases 3 and 4 should be promoted in architectural design under similar weather conditions as those in the study area, while case 5 should be avoided.

3.2. Effect of greening coverage on PM10 concentrations

The layout of the line source and wind direction in the utilized model is shown in Fig. 14**(d).** The analysis results of Section 3.1 that Case 4 had the best thermal effect on pedestrians. The higher the height of vegetation was, the less dust was retained by vertical greening due to the increasing distance from the pollution source. In case 4, both the pedestrian-level greening façade coverage rate and the near-pedestrian-level greening façade coverage rate 100%. Therefore, only case 4 and control group (case 1) were simulated and analysed.

As shown in Fig. 14, the results derived for cases 1–4 suggested that VGSs can reduce the pedestrian-level *PM10* concentrations in street canyons, but the dust reduction effects were not very significant. The maximum *PM10* concentration in the non-greening group (case 1) was 34.12 μg/m3 at a 1.5 m height at 14.00, and the minimum pollutant concentration was 33.99 μg/m3. In case 4, the maximum *PM10* pollutant concentration was 33.12 μg/m3 and the minimum pollutant concentration was 32.99 μg/m3. After comparing case 1 to case 4, it can be found that the maximum and minimum concentration changes were reduced by only about 1 μg/m3 at pedestrian level. This result is similar to the findings of a previous study (Buccolieri et al., 2018) in which the authors concluded that under parallel winds, the contribution of greenery to particulate deposition is negligible; of course, this effect varies with location and weather conditions.

Fig. 15 shows the vertical distribution of *PM10* concentration changes on the wall in the east-west street direction of Case 1,Case 4 and Case 1- Case 4 at 14:00. The *PM10* concentration distributions of Case 1 and Case 4 on the wall surface were similar, and the concentrations decreased with the increase of buildings height. The maximum and minimum *PM10* concentrations of case1 are 34.14 μg/m3 and 33.99 μg/m3, and the maximum and minimum *PM10* concentrations of case4 are 33.14 μg/m3 and 32.99 μg/m3, respectively. Numerically, this is similar to the *PM10* concentration at pedestrian level. Case 1- Case 4 is the vertical distribution change of *PM10* concentration difference on the wall with or without greening. In the vertical direction, the maximum and minimum *PM10* concentration changes are also very close to 1 μg/m3, which is numerically also similar to the horizontal change in pedestrian level. However, it can still be seen from the figure that as the height of the building increases, the change in *PM10* concentration gradually decreases. Because the farther away from the pollution source, the lower the concentration of pollutants, the contact between vertical greening and pollutants is limited, and the amount of change is also reduced accordingly (Mao et al., 2020). In addition, from Case 1-Case 4, it can be seen that the *PM10* concentration is layered vertically near the wall at about 6 m from the ground. On the one hand, it is because case 4 only arranges vertical greenery within a height of 6 m, and on the other hand, the concentration of pollutants gradually decreases due to the increase in the height of the building.

Although the results of this study indicate that VGSs have little effect on *PM10* concentrations, this does not mean that the VGSs cannot improve air quality under other conditions. Reducing pollutants with VGSs depends on various factors, including the plant species (Weerakkody et al., 2017; Tomson et al., 2021a, 2021b), wind direction and street canyon scale (Morakinyo et al., 2016; Zhang et al., 2021), leaf area index and humidity (Joshi and Ghosh, 2014). These factors also represent the directions that need to be explored in further research.

4. Conclusions

While innovations in vertical greening strategies are vital for providing environmentally friendly, resistant and sustainable cities, in this study, we analysed the outdoor thermal impacts of different greening façade arrangements and briefly analysed the effects of VGSs on *PM10* concentrations.

In this study, both field-measured and simulated datasets were used to provide scientific evidence regarding the thermal benefits of different façade greening arrangements. The analysis and spread of the urban street canyon concept require the use of accurate simulation models that can reliably predict the specific microclimate of the analysed space. This paper focuses on numerically modelling semi-enclosed spaces in street canyons with ENVI-met software and a model validation process. Through these methods, we evaluated five different greening façade scenarios to improve the pedestrian-level daytime thermal comfort as

1) Different façade greening arrangements have different impacts on outdoor thermal comfort. The greatest *MRT* reduction, a reduction of 1.41 ◦C, was achieved by arranging all greenery on

the lower half of the façade near the pedestrian level. While maintaining a constant total leaf area on the façade, increasing the pedestrian-level greening façade coverage could improve thermal comfort in the analysed urban street canyon. The most significant reduction in the average *PET* value (0.49 ◦C) was achieved by arranging all greenery on the lower half of the façade near the pedestrian level, while the smallest reduction in the average *PET* value (0.14 ◦C) was achieved by arranging all greenery on the top half of the façade.

2) While green coverage is essential for thermal comfort, ensuring the correct placement of VGSs is more important factor for obtaining the maximum thermal dividends. As a result, the total leaf area on the façade was not the only indicator of the impact of the greening façade on the thermal comfort in the street canyon. In our study, the placement of vertical greening at the bottom of the building (at a height of 3 m; although the heights presented herein are based on the modelling results, the conclusions are consistent with existing studies based on both measurements and modelling results in the tropics and other mid-latitude regions) results in a better reduction effect in the surface temperature during peak daytime temperatures than that obtained when greenery is placed at other heights. Therefore, the greening façade coverage at and near the pedestrian level significantly impacts the thermal comfort in the street canyon. Increasing the bottom-layer greening façade coverage enhances the greening-induced cooling effect, as reflected in the thermal comfort, within street canyons.

3) As far as this study was concerned, when the incoming wind direction was parallel to the building, the contributions of VGSs to pedestrian-level *PM10* concentrations were minimal, but positive effects were still observed. Case 4 induced the best thermal effect for pedestrians, followed by case 3. Therefore, the greening arrangement of the façade in case 4 was optimal in terms of the resulting thermal effect and dust reductions. Case 2 and case 6 exhibited similar thermal effects, but the layout represented by case 6 seemed to have a better façade beautification effect. Finally, layouts similar to that represented by case 5 should be avoided.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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