Science of the Total Environment 953 (2024) 176044

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Understanding the impacts of street greening patterns and wind directions on the dispersion of fine particles

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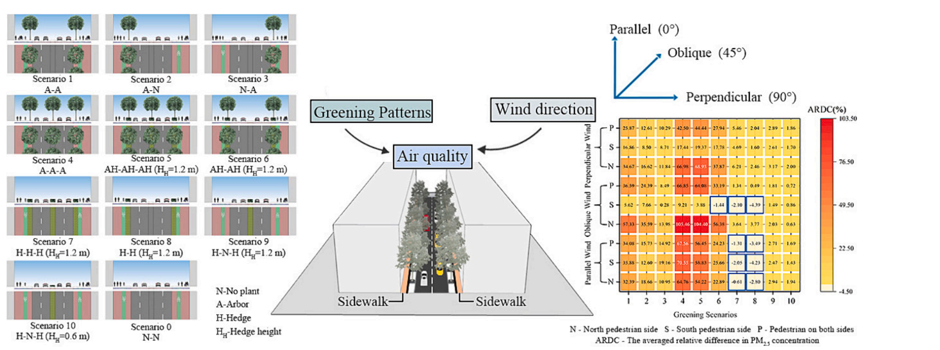
HIGHLIGHTS

- Horizontal and vertical distribution of $PM_{2.5}$ varied with different wind directions.
- Greening patterns and wind direction jointly impacted $PM_{2.5}$ dispersion in canyon.
- Optimal layout included unilateral-trees on windward side or two rows of hedges.
- ARDC was significantly correlated ($p < 0.01$) with most of the 3D green indicators.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Alessandra De Marco

Keywords:
Street canyon
$PM_{2.5}$
Green infrastructure
ENVI-met
Urban design

ABSTRACT

Inappropriate planting patterns can increase pollutant concentrations and threaten human health. This study examined three greening patterns (trees, trees + hedges, and hedges) using the ENVI-met model to evaluate the different effects of various planting patterns on $PM_{2.5}$ dispersion within an idealized 3D street canyon under three typical wind directions. Results showed that street greenbelts alter the $PM_{2.5}$ concentration field within canyons, and the horizontal and vertical distribution characteristics of $PM_{2.5}$ under different wind directions were significantly different. The arbor-hedge vegetation structure showed the highest total vegetation deposition amount due to larger canopy volumes while hedges have better deposition amounts per unit volume due to their proximity to emission sources. Additionally, this research selected the averaged relative difference in $PM_{2.5}$ concentration (ARDC) indicator to assess the influence of different green scenarios on the dispersion of $PM_{2.5}$ concentrations. Wind direction and planting patterns jointly affect the dispersion of $PM_{2.5}$ in canyons, and the ARDC varied from −4.39 % to 105.36 %. Unilateral-trees on the windward side or two rows of hedges may be the

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https://doi.org/10.1016/j.scitotenv.2024.176044
Received 10 July 2024; Received in revised form 24 August 2024; Accepted 3 September 2024
Available online 4 September 2024

optimal vegetation layout by trade-off with other services. ARDC was significantly correlated ($p < 0.01$) with most of the 3D green indicators. These results could provide effective suggestions for optimizing the layout of greenbelts in street canyons to improve air quality.

1. Introduction

With increasing global industrialization and urbanization, air quality has become a critical issue for many cities worldwide (Kumar et al., 2015; Fellini et al., 2022). $PM_{2.5}$ is an essential component of air pollutants representing the Air Quality Index (AQI), and has substantial adverse effects on atmospheric visibility (Sun et al., 2020), regional climate (Yang et al., 2020), human behavior (Chen et al., 2021a) and health (Feng et al., 2016). Traffic emissions have surpassed industrial emissions and become an important source of $PM_{2.5}$ pollution (Hama et al., 2020; Oroumiyeh et al., 2022). The urban street canyon is a critical environment for the generation and accumulation of pollution from traffic in urban areas (Kumar et al., 2021). It is also one of the primary places where urban residents most frequently engage in outdoor activities. Roadside pedestrians and residents are often exposed to high concentrations of particulate pollutants from traffic emissions, which pose serious health threats (Wang et al., 2021; Yan et al., 2024). Thus, it is essential to implement appropriate strategies to reduce traffic-related air pollution in street canyons.

Street vegetation can affect the distribution and concentration of particulate matter (PM) through aerodynamic and depositional effects (Zhang et al., 2021), and has been considered as a potential passive control strategy for purifying the street air (He et al., 2023). However, some studies have suggested that street vegetation may be a controversial strategy for improving air quality within urban streets (Xu et al., 2023), if not properly designed. Some studies related to aerodynamic effects have shown that the introduction of plants affects street ventilation, leading to increased street pollutant concentrations and ultimately worsening air quality (Vos et al., 2013). Some researches reported that plants can absorb and retain PM via deposition, contributing to air purification (Wu et al., 2021), and the attenuation effect varied with tree layout and PM sizes (Hashad et al., 2020; Ren et al., 2023). The impact of street greenbelts on PM dispersion depends on the comprehensive effect of street morphology, plants and meteorological conditions (Kumar et al., 2022; Kang and Kim, 2023; Barwise et al., 2024). This uncertainty could lead to inappropriate planning decisions, such as proposing inappropriate strategies for plant species selection and layout (Guo et al., 2023). Furthermore, street greening has a significant impact on the creation of livable cities (Fellini et al., 2022). Exploring the most appropriate vegetation layout may be a better way to address the aforementioned problems.

Individual plant characteristics (e.g., morphology and leaf area density (LAD)) (Guo et al., 2023), vertical community structure (e.g., shelterbelt porosity and canopy density) (Chen et al., 2021b), and horizontal layout of the vegetation barriers could significantly affect PM dispersal (Ren et al., 2023). In reality, vegetation barriers typically consist of multiple types of vegetation (Shen et al., 2023). While previous simulations have primarily focused on isolated factors such as vegetation species, crown characteristics, planting distance, tree height, leaf area index (LAI), LAD, or porosity, studies investigating the combined effects of different plant species and spatial arrangements of greenbelts are severely lacking. Therefore, it is crucial to systematically investigate the influence of mixed vegetation configurations that reflect the real situations found in urban areas. Furthermore, existing researches have generally focused on the 2D parameters of street greenbelts (Hong et al., 2017), with little consideration given to the 3D perspective. There is an urgent need to address this knowledge gap.

Wind direction is an important factor in assessing the impact of vegetation barriers on air quality in street canyons (Morakinyo et al., 2016), and has an apparent effect on the dispersion of $PM_{2.5}$ (Dos Santos-Juusela et al., 2013). Kumar et al. (2022) reported that the pollutant concentrations behind hedges varied with wind direction, and even presented opposite results for different wind directions. Furthermore, wind direction had a significant effect on self-ventilation within street canyons, and the ventilation capacity decreased with the addition of α (Jon et al., 2023). Meanwhile, the presence of trees may be the most important factor influencing the local wind field (Ren et al., 2023). Nevertheless, the coupled effect of green patterns and wind direction has rarely been considered in previous studies.

Despite some work was done on the mechanism of the influence of vegetation or wind direction on air pollution, research on the combined effects of green patterns and wind direction on $PM_{2.5}$ dispersion needs further exploration. This study aims to explore the effects of different green scenarios and wind directions on $PM_{2.5}$ deposition and dispersion in urban street vegetation and sub-arterial roads in Taiyuan, China. The research uses ENVI-met simulation within an idealized 3D street canyon, which is characterized by the highest concentration of $PM_{2.5}$ compared to shallow streets or deep streets (Kumar et al., 2019). This investigation seeks to answer the following questions: (1) What are the spatial distribution characteristics of $PM_{2.5}$ concentrations with different green scenarios under three typical wind directions? (2) Is there a variation in the amount of vegetation deposition under different green scenarios? (3) What is the optimal greenbelt configuration or layout to improve the street air quality based on evaluating the relative concentration changes of different green scenarios from different angles (windward pedestrian side, leeward pedestrian side, and pedestrian on both sides) on $PM_{2.5}$ dispersion? (4) What are the correlations between 3D street green indicators and the average concentration difference of $PM_{2.5}$?

2. Methodology

2.1. Study area

Taiyuan (112°56′ E, 37°87′ N) is the capital of Shanxi Province, and has a population over 5.43 million by 2022. The city has a monsoon climate, with southeast winds prevailing in the summer. Additionally, Taiyuan has seen a steady increase in the number of motor vehicles over the years. By 2021, the total car ownership exceeded 1.8 million, representing a ratio of approximately one car for every three individuals. This escalation in vehicle counts has led to urban traffic congestion and a consequent increase in traffic-related emissions. The annual average concentration of $PM_{2.5}$ in Taiyuan is 45 μg m^{-3} in 2021, which is obviously higher than the health standard for $PM_{2.5}$ set by China (35 μg m^{-3}) and also greater than the target value set by the World Health Organization (WHO). Therefore, it is imperative to enhance the urban air quality and the pedestrian travel environment.

2.2. Green pattern design

This study considered the significance of sub-arterial streets, which serve as crucial spaces for both pedestrian and traffic activities. *Sophora japonica* and *Euonymus japonicas*, the most common tree or hedge species in Taiyuan, China, were chosen as the prototype for the numerical simulation plant model. Based on the previous investigation results (Pei et al., 2023), the growth parameters of the trees were set as height 8 m, crown width 7 m, planting spacing 6 m, and LAD 1.5 m^2 m^{-3}. Hedges were set at heights of 0.6 m and 1.2 m, respectively, with a width of 2 m and an LAD of 2.5 m^2 m^{-3}.

Based on the previous field survey of the green patterns in Taiyuan and other related design projects, three green patterns (10 green scenarios) were designed (Fig. 1). The detailed green patterns include only-tree green patterns (S1–4): two rows of trees, one row of trees and three rows of trees), mixed configuration of trees and hedges (S5–6): two rows of mixed configuration and three rows of mixed configuration), and only-hedges (S7–10): three rows of hedges with 1.2 m height, two rows of hedges with 1.2 m height, and only central hedges with 1.2 m and 0.6 m height, respectively).

2.3. ENVI-met model

ENVI-met is a 3D urban microclimate model that uses computational fluid dynamics (CFD) and thermodynamics to simulate the intricate interactions between vegetation, building surfaces, and the atmosphere at the micro-scale (Hofman et al., 2016). The fluid solution is based on the Reynolds-Average Navier-Stokes (RANS) equations. Meanwhile, the E-ε model is used to characterize the turbulence (Guo et al., 2023). ENVI-met simulates the dispersion of gases and particles using the Euler method. It includes the sedimentation and deposition of particles on surfaces and leaves (Guo et al., 2023). It also provides predicted values and spatial distributions of key parameters such as wind speed, pollutant concentration, vegetation view factor (VVF) and sky view factor (SVF). In particular, ENVI-met excels in vegetation simulation compared to other CFD software (Liu et al., 2021), enabling it to simultaneously simulate PM diffusion, dry deposition, and PM deposition within plant canopies (Wania et al., 2012). Over the past few years, ENVI-met has gained wide acceptance and application in studies related to pollutant dispersion (Deng et al., 2019; Guo et al., 2023). This research used ENVI-met V5.0.3 to simulate the dispersion of $PM_{2.5}$ under different green patterns and three typical wind directions.

2.3.1. Validation

The simulation accuracy of the $PM_{2.5}$ concentration was verified by comparing the measured and ENVI-met simulated results. Wucheng North Street, an east-west oriented street in Xiaodian District, Taiyuan, was selected for this study (Fig. 2A). From 07:00 h to 16:00 h (local time) on July 21, 2022. The data of $PM_{2.5}$ concentration (by Aerocet 531 s, America Metone), meteorological data (by Kestrel 5500, America), and traffic flow (by video camera) per hour were measured. And the averaged data for each hour during the measurement were used. Additionally, the characteristic parameters of street canyon and trees were also investigated. $PM_{2.5}$ concentration and meteorological data were measured simultaneously at two locations, one under the street trees and the other at a reference (no tree) location on the sidewalk.

The characteristics of tree and street morphology of the validation model were obtained from field measurements (Fig. 2B), the background meteorological data (wind speed and direction, hourly air temperature and relative humidity of the day) were obtained from the China Meteorological Data Service Centre (https://data.cma.cn), and the pollutant emission rates were calculated by multiplying the measured traffic flow and the emission factor (Xu and Zhou, 2012). Detailed simulation parameters of the validation experiment were described in Appendix Table A1.

The $PM_{2.5}$ dimensionless value of the field measurement and the numerical simulation were compared (Fig. 2C). The correlation coefficients (R^2) and root mean square error (RMSE) between the measured and simulated $PM_{2.5}$ dimensionless values at the reference site are 0.83 and 0.17, respectively. Meanwhile, the two values at the measured site are 0.87 and 0.17. According to the validation results of previous studies (Hofman and Samson, 2014; Wu et al., 2021), the validation results showed acceptable accuracy and precision.

2.3.2. Grid sensitivity analysis

A grid sensitivity test of the model was carried out. In order to maintain result comparability, the simulations were performed with three spatial grid sizes: fine (1 m × 1 m), medium (2 m × 2 m) and coarse (4 m × 4 m). All grid sizes were conducted under consistent physical and boundary conditions (Jin et al., 2024). We have compared the simulation results of medium (2 m × 2 m) and coarse (4 m × 4 m) grids with fine (1 m × 1 m) grids (Fig. 3). Based on the following results, the medium grid (2 m × 2 m × 3 m) was selected in this research as the $PM_{2.5}$

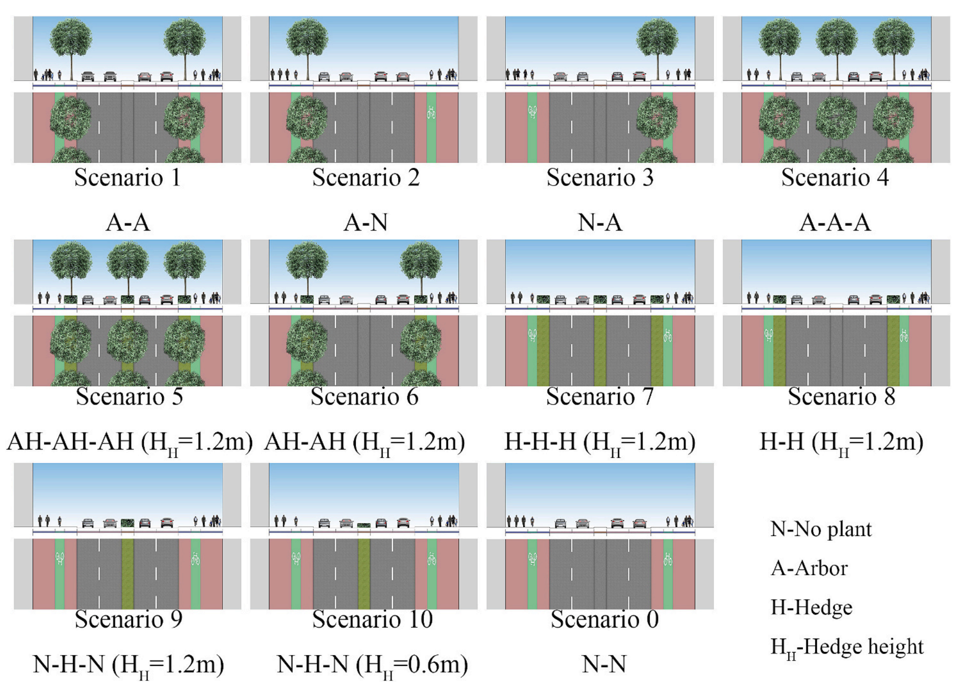

Fig. 1. Vertical and plane views of different greening scenarios. (S1) Arbors planted on both sides of the street; (S2) Arbors planted on the north side; (S3) Arbors planted on the south side; (S4) Arbors planted on both sides and in the center of the street; (S5) Arbors and hedges planted on both sides and in the center of the street; (S6) Arbors and hedges planted on both sides of the street; (S7) Hedges planted on both sides and in the center of the street; (S8) Hedges planted on both sides of the street; (S9) Hedges planted in the center of the street; (S10) Hedges planted in the center of the street at half the height of the hedges in the other scenes; (S0) No plant.

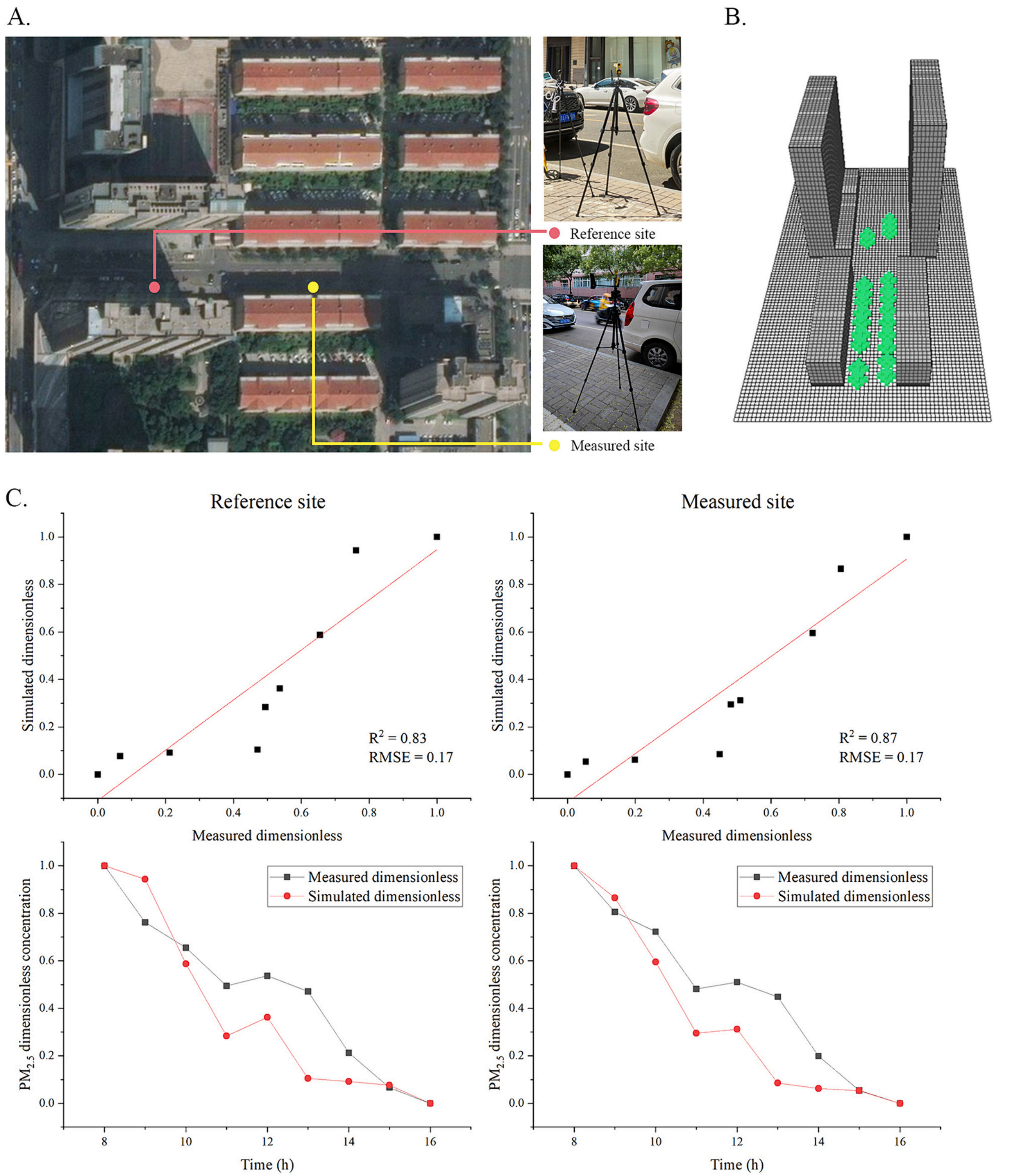

Fig. 2. Field experiment location, process, and comparison between measured and simulated (A. Field measurement site; B. ENVI-met model; C. Fitting and comparison of measured and simulated dimensionless value at no-tree reference site and with-tree measured site).

concentration on the windward and leeward sides was almost similar, and the excessive computational cost of finer meshes was considered.

2.3.3. Simulation project

In the simulation project, three wind directions of parallel wind, oblique wind and perpendicular wind (α = 0°, 45°, 90° respectively) and three green patterns (10 green scenarios) were set. A total of 30 scenes with vegetation and 3 scenes without vegetation were tested. In terms of computational domains, the model area spanned along the X, Y and Z axes is 55, 85 and 30 grids, respectively. The grid dimensions were 2 m × 2 m × 3 m and all grids were of the same height, except that the bottom grid was divided into five equal sections along the *Z*-axis to increase precision (Yang et al., 2018). Additionally, 10 nested grids were added at the boundary. In terms of the meteorological conditions, the hourly air temperature and humidity from the China Meteorological Data Service Centre on July 31, 2021 (no rain in the previous week)

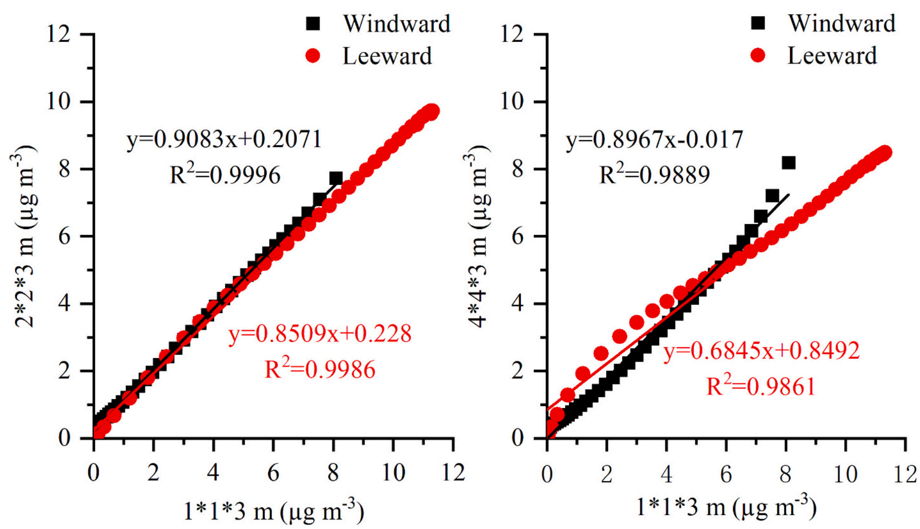

Fig. 3. Grid sensitivity analysis of windward and leeward $PM_{2.5}$ concentration.

were selected. Average wind speed of 2 m s^{-1} was set. The pollution source was set as a two-line source in the central of the street, and its parameters were determined by reference (Xu and Zhou, 2012), and the $PM_{2.5}$ emission rate was set to 33.56 μg m^{-1} s^{-1}. The simulation started at 6:00 am on July 31, 2021 and lasted for 12 h. The material properties of the buildings, roadways, sidewalks, and planting beds were determined by field experiment and using the existing material database of the ENVI-met software. Further detailed parameter settings are shown in Fig. 4.

2.4. Data analysis

2.4.1. $PM_{2.5}$ concentration difference indicator

In this study, the average $PM_{2.5}$ values on both sides of the sidewalks at different heights (h = 0.3 m, 0.9 m, 1.5 m, 2.1 m, 2.7 m, 4.5 m, 7.5 m, 10.5 m, 13.5 m, 16.5 m, 19.5 m, 22.5 m, 25.5 m and 28.5 m) above the ground at 18:00 h (the peak time and with a large flow of people) were extracted for analysis. The averaged relative difference in $PM_{2.5}$ concentration (ARDC) indicator was adopted to assess the influence of

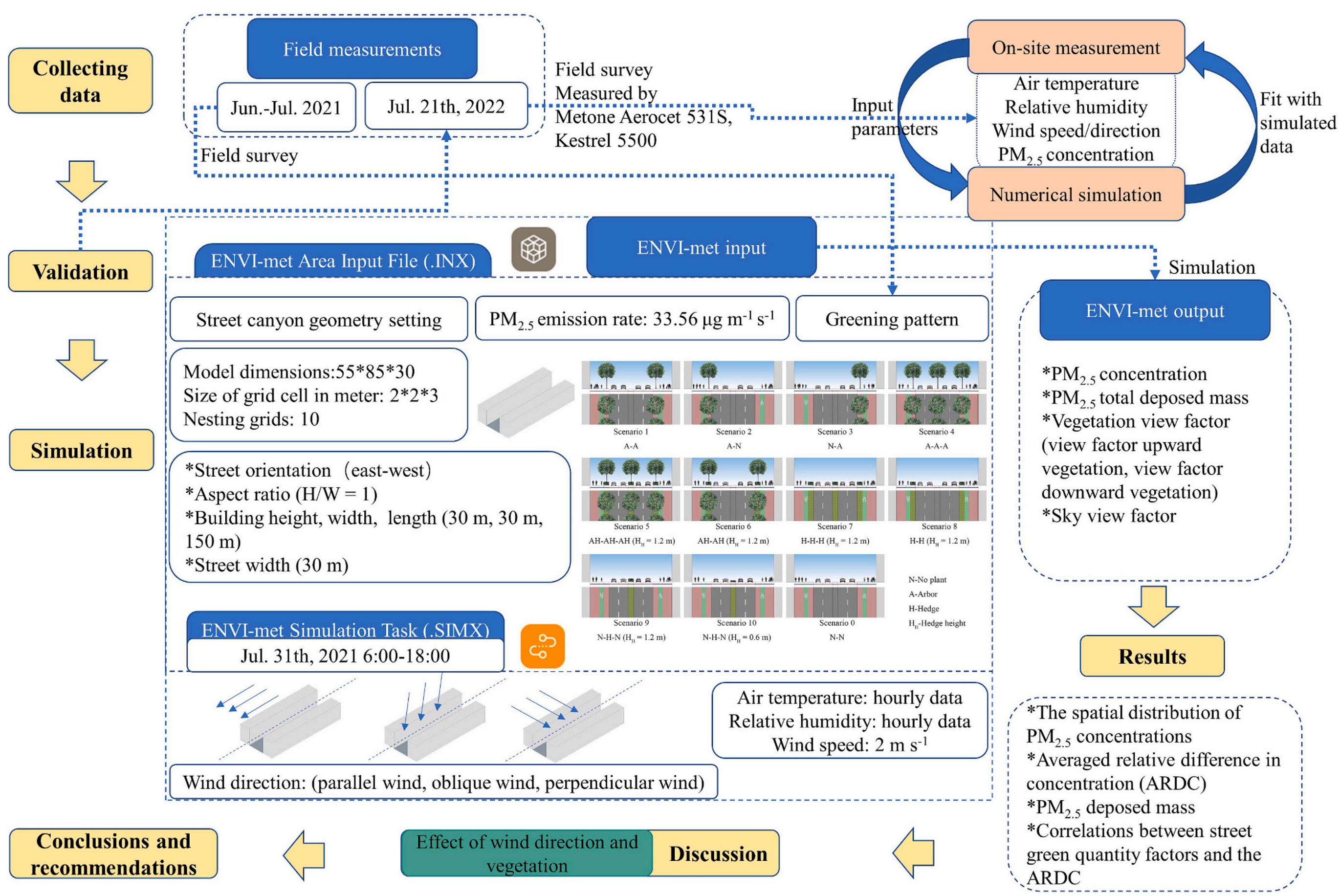

Fig. 4. Methodological framework of this study.

different green scenarios on the dispersion of $PM_{2.5}$ concentrations, which calculated the relative change rate (%) per scenario with vegetation and the reference scenario without plants (Morakinyo et al., 2016; He et al., 2023). A positive rate (+ %) of ARDC indicates that vegetation could increase the $PM_{2.5}$ concentration, and the greater the value, the more severe the deterioration. The opposite is true for a negative rate (− %) of ARDC.

$$ARDC = \frac{1}{n}\sum_{i=1}^{n}\frac{C_{veg}-C_{ref}}{C_{ref}}\times 100\% \qquad (1)$$

where i is the grid cell and n is the number of grid cells in the sidewalk. C_{veg} and C_{ref} are the $PM_{2.5}$ concentrations with and without vegetation, respectively.

2.4.2. Green indicators

To explore the correlation between greening indicators and $PM_{2.5}$ ARDC, and to determine which parameter of vegetation structural characteristics has an obvious influence on the air quality of sidewalks. Green volume ratio (GVR), green plot ratio (GPR) (Guo et al., 2021), and VVF were adopted. In addition, SVF is also introduced. SVF not only incorporates the characteristics of the amount of vegetation, but also takes into account other multiple visual obstacles in the street environment. In particular, roadside trees and building structures along the street could affect the dynamic dispersion of PM within the street canyons (Hu et al., 2021). The VVF and SVF in the central of the street and sidewalks at 1.5 m height can be calculated and extracted in ENVI-met.

$$GVR = V_v/V_{sc} \qquad (2)$$

V_v is the total volume of the vegetation canopy (m^3), and V_{sc} is the volume of the street canyon (m^3).

$$GPR = (LAD_aV_a + LAD_hV_h)/A_{sc} \qquad (3)$$

LAD_a is the LAD of the arbor (1.5 $m^2\ m^{-3}$), V_a is the total volume of the arbor canopy (m^3), LAD_h is the LAD of the hedge (2.5 $m^2\ m^{-3}$), and V_h is the total volume of the hedge (m^3). A_{sc} is the area of the street canyon (m^2).

3. Results

3.1. Spatial distribution of $PM_{2.5}$ concentration

3.1.1. Horizontal distribution

The horizontal distribution of the concentration of $PM_{2.5}$ at the breathing height (1.5 m above the ground level) varied in the different scenarios (Fig. 5). Under the parallel wind direction, the $PM_{2.5}$ concentration exhibited an almost symmetrical distribution along the middle axis of the street canyon. However, the leeward $PM_{2.5}$ concentrations were higher than windward in both oblique and perpendicular wind directions, and the concentration of $PM_{2.5}$ was higher in the central of the street. Furthermore, when compared to scenarios without plants, most street canyons with vegetation showed increased $PM_{2.5}$ concentrations to varying degrees.

Additionally, this investigation further quantified the $PM_{2.5}$ concentration at the breathing height (1.5 m above the ground level) of sidewalk on the north side, the south side and the mean of both sides (Fig. 6). Regarding the same green pattern, the $PM_{2.5}$ concentration in descending order was perpendicular wind (Fig. 6C) > oblique wind (Fig. 6B) > parallel wind (Fig. 6A). The $PM_{2.5}$ concentration on each side was decreased with decreasing number of tree rows, i.e., three rows of trees (S4) > two rows of trees (S1) > one row of trees (S2 and S3). The $PM_{2.5}$ concentration of each side did not obviously change with different numbers of rows (S7, S8 and S9) and height (S9 and S10) of hedges.

The diffusion characteristics of $PM_{2.5}$ concentrations among different configuration structures were different. Under the parallel wind ($\alpha = 0°$), the lowest mean $PM_{2.5}$ concentrations at the breathing height was found in S8 (5.78 ± 3.14 μg m^{-3}), and the highest was in S4 (10.03 ± 4.88 μg m^{-3}) (Fig. 6A). The $PM_{2.5}$ concentrations on the north and south sidewalks do not differ noticeably. Under oblique wind ($\alpha = 45°$) and perpendicular wind ($\alpha = 90°$), the average concentration of leeward side (north sidewalk) is obviously higher than windward side (south sidewalk). The lowest average $PM_{2.5}$ concentration at the pedestrian breathing height was in S0 (6.86 ± 3.30 μg m^{-3}) and the highest in S4 (11.45 ± 7.15 μg m^{-3}) under the oblique wind ($\alpha = 45°$) (Fig. 6B). The lowest mean $PM_{2.5}$ concentration on the pedestrian breathing level was in S0 (10.92 ± 1.97 μg m^{-3}), and the highest was in S5 (15.77 ± 4.29 μg m^{-3}) under the perpendicular wind ($\alpha = 90°$) (Fig. 6C).

3.1.2. Vertical distribution

$PM_{2.5}$ concentrations gradually decreased with increasing vertical height within the street canyons (Fig. 7 and Appendix B), while the vertical decrease in $PM_{2.5}$ concentration varied with wind direction and spatial position. Specifically, the impact of street green patterns was transferred to the upper level (yellow bands in Fig. 7, which means almost no difference among different scenarios) on the leeward side (the north side) of the street canyons. However, in the case of oblique and perpendicular wind directions, street greening was no longer effective on the windward side when vertical heights >8 m (almost the height of the arbor canopy) (green band in Fig. 7). The vertical decrease rule of the $PM_{2.5}$ concentrations on the north and south sides showed a similar pattern under parallel wind direction.

3.2. Deposition effect

3.2.1. Total $PM_{2.5}$ deposition

The effect of vegetation deposition on the different scenarios was examined by summing the deposition per unit area of each green scenario in five height layers (Fig. 8A). The green scenario with the arbor-hedge configuration structure has the highest deposition amount. For each wind direction, the combination of trees and hedges (S5) has the highest total $PM_{2.5}$ deposition. Under three wind directions, the minimum value is 12.07 mg in S10 for parallel wind, 10.81 mg in S10 for oblique wind and 6.31 mg in S10 for perpendicular wind, respectively.

3.2.2. $PM_{2.5}$ deposition per unit volume

The ratio of total $PM_{2.5}$ deposition to the total volume of the vegetation grid was used to analyze the dust retention capacity per unit volume of each planting pattern (Fig. 8B). In each wind direction, S3 has the minimum value of $PM_{2.5}$ deposition per unit volume, and S10 has the maximum value of $PM_{2.5}$ deposition per unit volume. Especially for the 45° wind, the maximum value is seven times higher than the minimum value.

3.3. $PM_{2.5}$ relative concentration difference of various greening patterns

To characterize the effect of different planting strategies on $PM_{2.5}$ concentrations at different locations within the street canyons, the averaged relative difference in $PM_{2.5}$ concentration at the sidewalks on the north pedestrian side (NARDC), the south side (SARDC), and both pedestrian sides (PARDC) of the street canyon were calculated. The ARDCs of different green scenarios under different wind directions are shown in Fig. 9. Overall, PARDC varied from 67.56 % for parallel wind to −3.49 % for parallel wind; NARDC varied from 105.46 % for oblique wind to −2.80 % for parallel wind; SARDC varied from 70.55 % for parallel wind to −4.39 % for oblique wind.

3.3.1. Parallel wind

PARDC ranged from 67.56 % to −3.49 %, NARDC ranged from 64.76 % to −2.80 %, and SARDC ranged from 70.55 % to −4.23 %. The only-hedge green patterns had lower PARDC, NARDC and SARDC values than the other scenarios. The highest PARDC was achieved by S4. The optimal vegetation configuration was two rows of hedges (S8): the

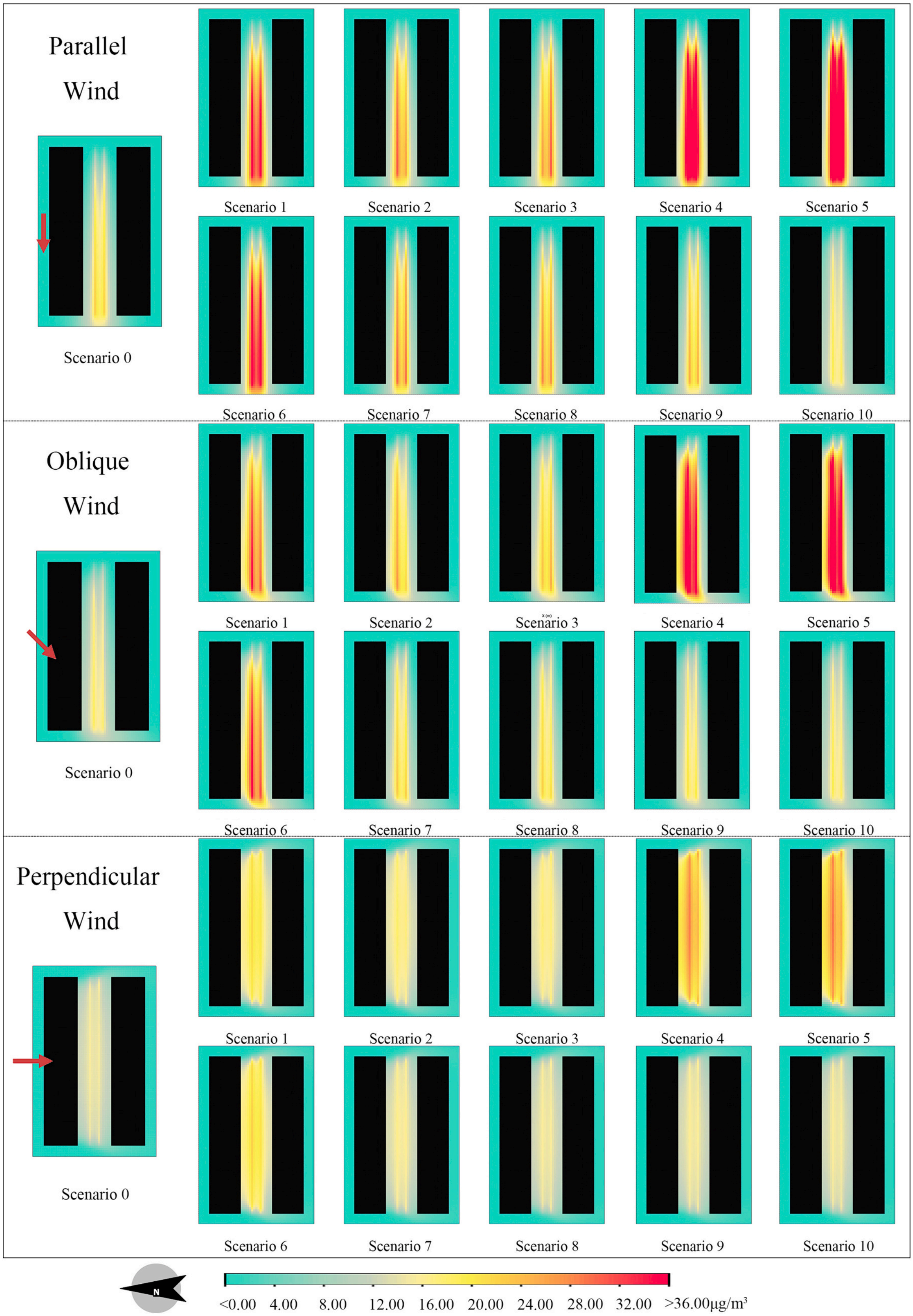

Fig. 5. The horizontal distribution of $PM_{2.5}$ at pedestrian breathing height (1.5 m). The red arrow indicates the direction of the incoming wind.

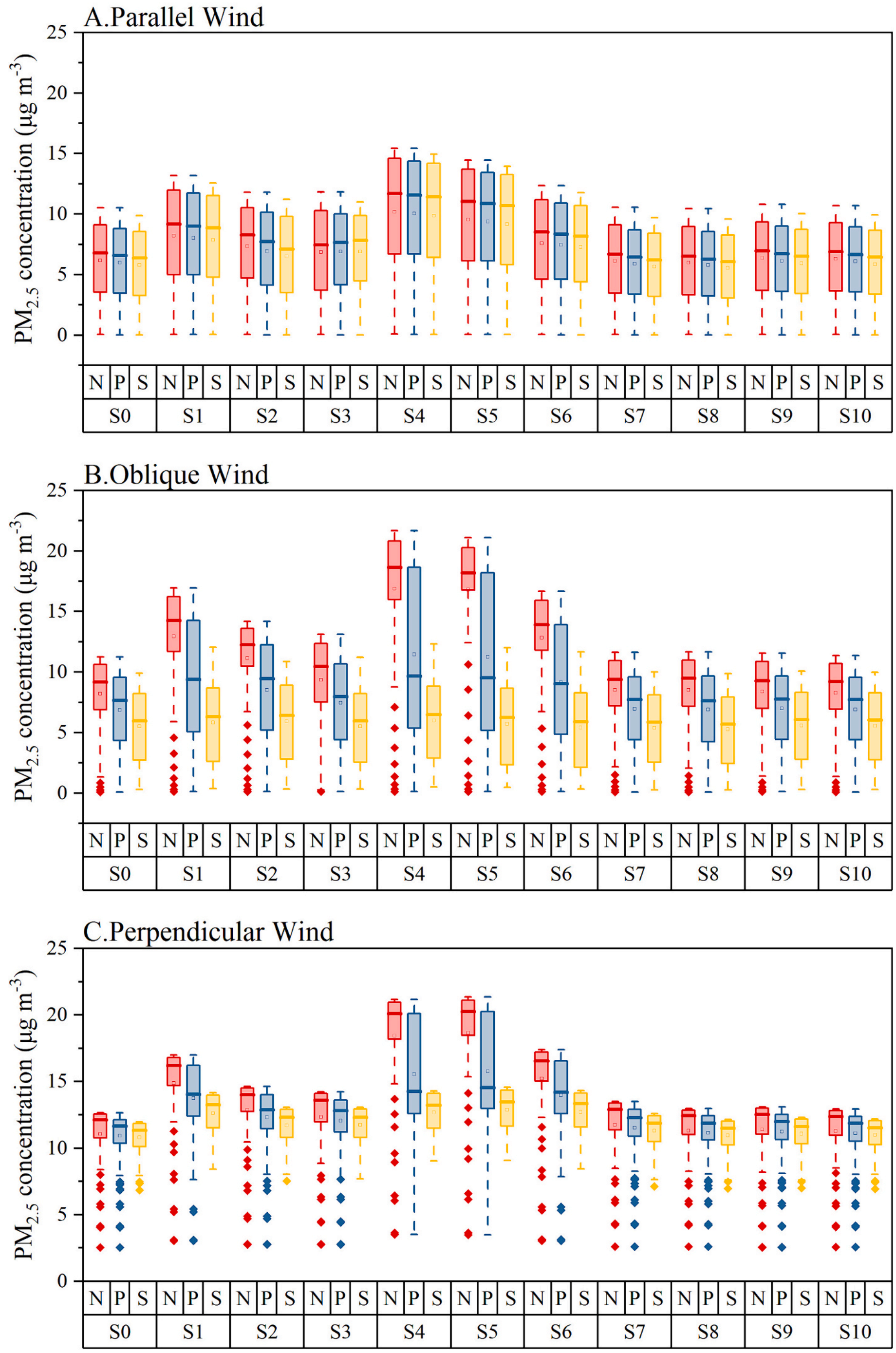

Fig. 6. Box plot comparing the distribution of $PM_{2.5}$ concentrations (μg m^{-3}) at different locations of street canyons. (A. under parallel wind, B. oblique wind, C. perpendicular wind. N - north pedestrian side, S - south pedestrian side, P - average impact on pedestrians on both sides.)

PARDC was up to −3.49 % and the NARDC and the SARDC were − 2.80 % and − 4.23 %, respectively.

3.3.2. Oblique wind

PARDC ranged from 66.85 % to 0.49 %, NARDC ranged from 105.46 % to 0.63 %, and SARDC ranged from 9.21 % to −4.39 %. The only-hedge planting patterns had the lower PARDC and NARDC than those of the other scenarios. The highest PARDC was found with S4, while the optimal vegetation configuration was two rows of hedges (S8): the PARDC, NARDC and SARDC were 0.49 %, 3.77 % and − 4.39 %, respectively. Regarding the only-tree cases, the PARDC and NARDC of the one row planting were better than the other scenarios. The maximum SARDC occurred in S4, followed by S2.

3.3.3. Perpendicular wind

PARDC ranged from 44.44 % to 1.86 %, NARDC ranged from 68.93 % to 2.00 %, and SARDC ranged from 19.37 % to 1.60 %. Under perpendicular wind, positive ARDC were found in all scenarios. The only-hedge planting pattern had the smaller PARDC, NARDC and SARDC than the other scenarios. The largest PARDC was found for S5. The optimal vegetation configuration was only central hedges (S10): the PARDC, NARDC and SARDC were 1.86 %, 2.00 % and 1.70 %, respectively.

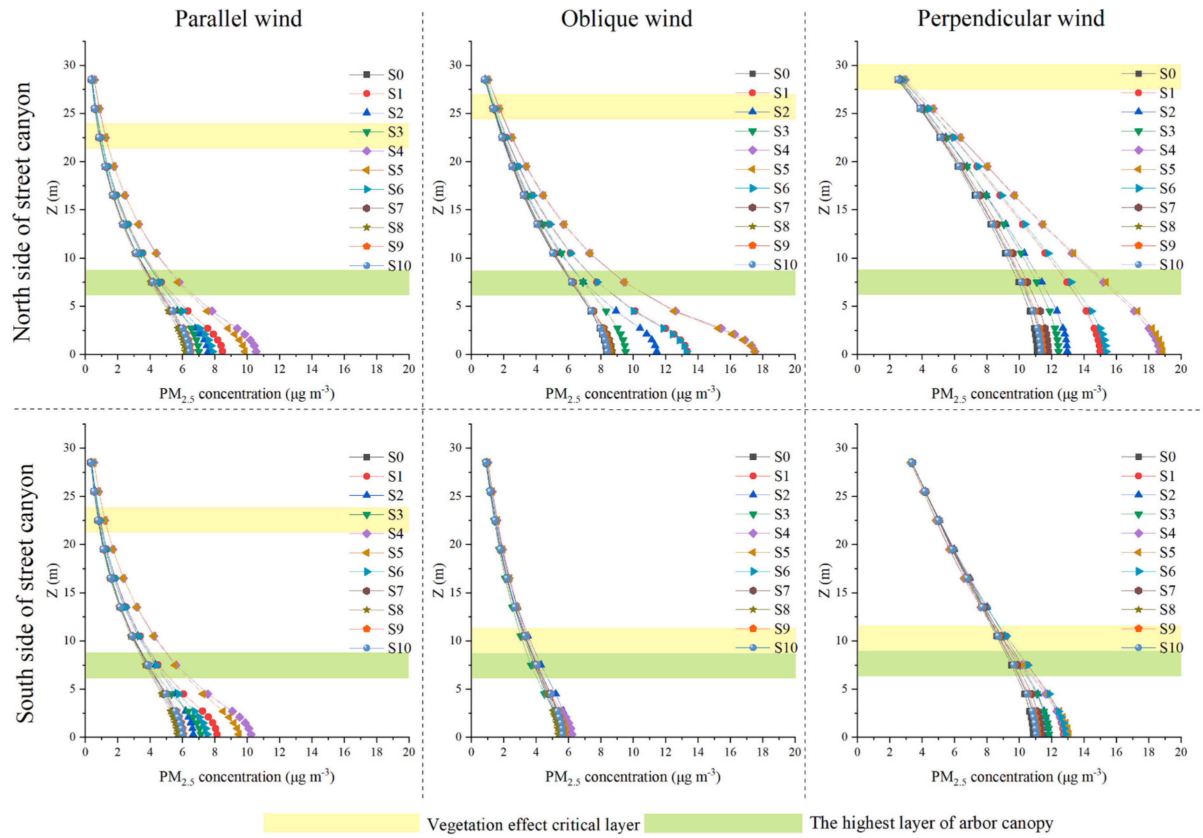

Fig. 7. The vertical distribution of $PM_{2.5}$ concentrations on two sides of street canyons under parallel wind (A and D), oblique wind (B and E), perpendicular wind (C and F).

3.4. Correlations between street green quantity factors and the ARDC

Based on the grid number of the numerical models, GVR, GPR, VVF and SVF, which are related to green quantity, were calculated in Table 1, and the correlations between these factors and the ARDC of $PM_{2.5}$ were analyzed (Fig. 10). PVVF and PSVF represent the vegetation view factor and the sky view factor at 1.5 m height on the pedestrian side of both sides of the street, while CVVF and CSVF represent the vegetation view factor and the sky view factor at 1.5 m height in the center of the street, respectively. As the green quantity factors mainly focused on the whole greening environment of the street, so we just analyzed the correlation between the mean values of both sides ARDC (PARDC) with the green quantity factors of street. The correlation analysis among the selected green quantity factors and the ARDC of $PM_{2.5}$ showed that the ARDC of $PM_{2.5}$ had a significant positive correlation with GVR, GPR, PVVF and CVVF and a significant negative correlation with PSVF and CSVF.

4. Discussion

4.1. Impact of wind direction on $PM_{2.5}$ dispersion within street canyons

Wind direction strongly influenced the spatial distribution of $PM_{2.5}$. For the same green scenario, the order of $PM_{2.5}$ concentration was perpendicular wind (Fig. 6C) > oblique wind (Fig. 6B) > parallel wind (Fig. 6A). Parallel wind is more conducive to pollutant transport in street canyons (Wu et al., 2021), and perpendicular wind is most detrimental to the removal of pollutants from the street canyons (Sabatino et al., 2008). Li et al. (2023) revealed that when the wind flow was parallel to the canyon axis, the flow regime was dominated by a parallel flow to the canyon axis, with little upward vertical deflection within the canyon (see in Fig. 6). When the wind flow was perpendicular to the axis of the canyon, there was a clockwise main vortex and the particles were trapped within the canyon (Park et al., 2022), leading to higher $PM_{2.5}$ concentrations of leeward than windward and higher $PM_{2.5}$ concentrations in the middle of the street than at the end. In the case of oblique wind, the superposition of parallel and perpendicular flows creates a spiral flow (Buccolieri et al., 2009), which transports and accumulates traffic pollutants along the street axis and leeward simultaneously. This investigation revealed that $PM_{2.5}$ concentration were higher during vertical wind than parallel wind (see in Fig. 7). Additionally, leeward $PM_{2.5}$ concentrations were significantly higher than windward concentrations for both oblique and perpendicular wind directions. Under parallel wind conditions, no significant difference in concentration was found between the north and south sides, but the northern concentration was consistently lower than the southern concentration, possibly due to the difference in air temperature (Miao et al., 2023).

Most studies mainly focus on the horizontal diffusion of pollutants in the lower layer of the street canyon or at pedestrian breathing height under different wind directions. This research employed numerical simulation to explore the pollutant diffusion characteristics in horizontal and vertical dimensions, which broadens the knowledge of the 3D spatial distribution of $PM_{2.5}$ within street canyons, which would help researchers and administrators to estimate exposure levels and improve air quality. It was found that the concentration of $PM_{2.5}$ within street canyons gradually decreased with an increase in the vertical distance from the ground, which is in line with Wu et al. (2021). Furthermore, the vertical decrease in $PM_{2.5}$ concentration varied with wind direction (Fig. 7). $PM_{2.5}$ would be carried to the upper level (>20 m, yellow band in Fig. 7) on the leeward side (north side), and would not obviously increase above 8 m (almost arbor canopy height) on the windward side of the 90°and 45° wind (green band in Fig. 7). Under 0° wind, the vertical decrease of $PM_{2.5}$ concentration showed a similar pattern on both sides. The above results indicate that low-rise residential buildings are heavily exposed to pollutants within street canyons, which could

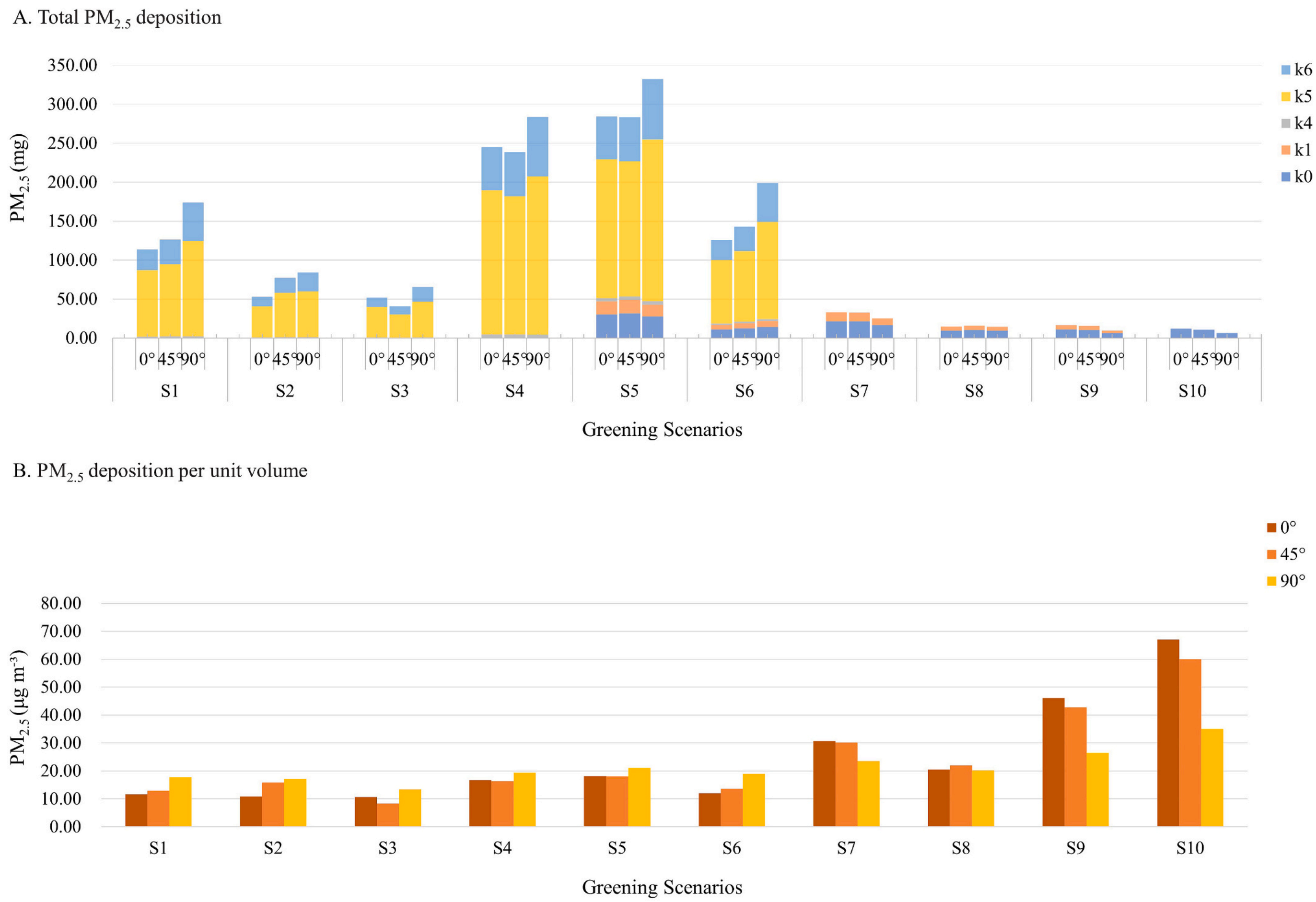

Fig. 8. Deposition effects under different winds. (A. total $PM_{2.5}$ deposition and B. $PM_{2.5}$ deposition per vegetation unit volume. k0, k1, k4, k5 and k6 represent vegetation grids with canopy heights of 0–0.6 m, 0.6–1.2 m, 2.4–3.0 m, 3.0–6.0 m, and 6.0–9.0 m, respectively.)

provide specific suggestions for urban planners or landscape designers and contribute to improving air quality.

4.2. Impact of the greenbelt layout on $PM_{2.5}$ dispersion

The relationship between street plant community factors and pollutant concentrations is complex and has not been fully understood by previous studies (Liu et al., 2023). This investigation indicated that plants can remove pollutants through sedimentation, the arbor-hedge configuration structure has the highest deposition amount due to its complex branches and large canopy volume (Jeanjean et al., 2016), and hedges have better deposition amount per unit volume due to proximity to the emission sources (Fig. 8), which is consistent with Wu et al. (2021). Additionally, plants increase street pollutant concentrations through aerodynamic effects by reducing mechanical turbulence and decreasing wind speed (Gonzalez Olivardia et al., 2021). Results demonstrated that $PM_{2.5}$ dispersion varies with green patterns (Fig. 5). In general, $PM_{2.5}$ concentration increased with increasing number of tree rows, as more tree rows occupy more street space, leading to lower wind velocity (Shen et al., 2023). Santiago et al. (2022) showed that trees in the central street would lead to a more obvious increase in air pollutant concentrations, especially under parallel winds, which is also confirmed in this research (S4 and S5 in Fig. 5). In most of the green cases, the aerodynamic effect led to increased $PM_{2.5}$ concentrations (Figs. 6 and 9), meaning that the effect of the street green scenarios on the dispersion of particulate matter exceeds the deposition effect (Hofman et al., 2016).

Green pattern design is more important than the quantity of vegetation for PM removal (Ren et al., 2023). In this investigation, planting hedges on both sides of the road had the best vegetation effect. Even when the volumes of vegetation were the same, the distribution of $PM_{2.5}$ concentrations were differed among different locations of vegetation planted within street canyons, as in S2 and S3. Those only-tree patterns significantly reduced wind speed, resulting in an increase in the $PM_{2.5}$ concentration (Vos et al., 2013), and one-sided planting was superior to those two-sided planting, especially on the windward side. The aforementioned results suggest that the location of planting may be more critical than the canopy cover and tree volume. Although the arbor-hedge structure has more total vegetation deposition, the aerodynamic effect surpassed the deposition effect, which may cause air quality deterioration (Jeanjean et al., 2016; Baldauf, 2017), thus planting dense trees in streets should be avoided to improve air quality. Earlier studies have reported that the presence of hedges is beneficial to air quality, as they deflect pollutants from sidewalk areas by creating localized eddies (Gromke et al., 2016; Kumar et al., 2022; Li et al., 2023). However, this investigation showed that the hedges had a relatively lower purifying effect for $PM_{2.5}$ than their larger counterparts, which is in line with Li et al. (2023), or even hindered the outward diffusion as the ventilation decreased (Vos et al., 2013). This investigation reported that the influence of hedges differed in different layouts or heights (Figs. 5, 7 and 8), the purification effect of two sidewise hedges may be the optimal selection, and the influence of hedges was reversed with increasing height. Last but not least, greening designers should take into account the characteristics of the road environment. In this investigation, the effects of greening design within street canyon on fine particles were examined. Conversely, the tree + hedge combination

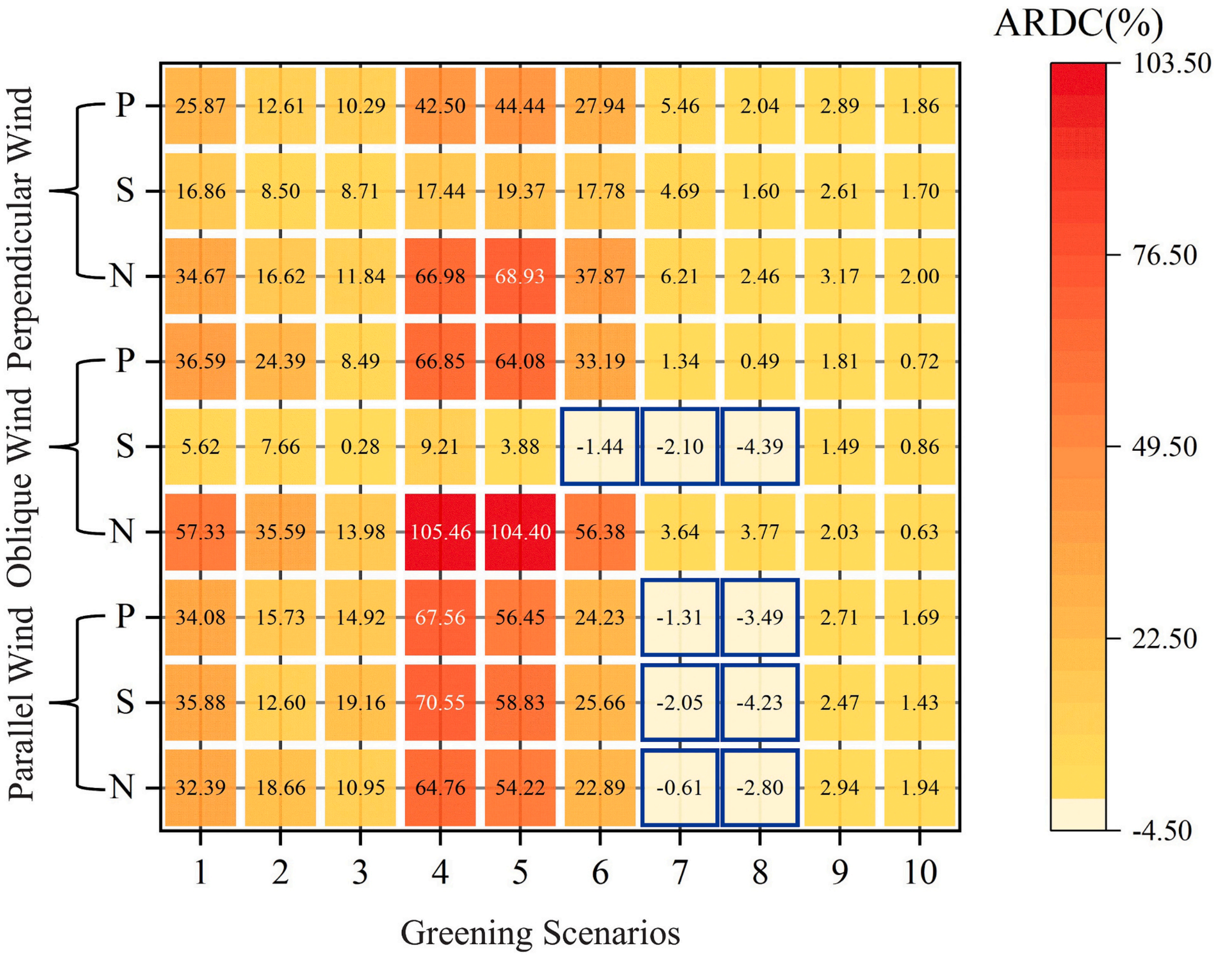

Fig. 9. Heatmap comparing ARDC (%) at different locations in street canyons with various scenarios. (N - north pedestrian side, S - south pedestrian side, P – average impact on pedestrians on both sides.)

Table 1
Green quantity factors of greening scenarios.

	GVR	GPR	PVVF	CVVF	PSVF	CSVF
S1	0.07	3.26	0.39	0.11	0.06	0.58
S2	0.04	1.63	0.20	0.06	0.29	0.59
S3	0.04	1.63	0.20	0.06	0.29	0.59
S4	0.11	4.88	0.39	0.47	0.06	0.05
S5	0.12	5.48	0.43	0.79	0.06	0.05
S6	0.08	3.66	0.41	0.13	0.06	0.58
S7	0.01	0.60	0.07	0.32	0.52	0.59
S8	0.01	0.40	0.06	0.03	0.52	0.59
S9	0.00	0.20	0.01	0.30	0.52	0.59
S10	0.00	0.10	0.01	0.17	0.52	0.59

GVR - green volume ratio. GPR - green plot ratio. PVVF - vegetation view factor at 1.5 m height on the sidewalks. CVVF - vegetation view factor at 1.5 m height in the center of the street. PSVF - sky view factor at 1.5 m height on the sidewalks. CSVF - sky view factor at 1.5 m height in the center of the street.

minimizes pollutants in open-road (Abhijith and Kumar, 2019).

4.3. *Impact of greening quantity on $PM_{2.5}$ dispersion*

From the above results (Fig. 10), GVR, GPR, and PVVF have significantly positive correlations ($p < 0.001$) with ARDC, and CVVF has a significantly positive correlation with ARDC at the 0.05 level ($p < 0.05$). SVF (PSVF and CSVF) was significantly negatively correlated with ARDC ($p < 0.001$). The results showed that the higher the amount of greening, the higher the rate of increase in $PM_{2.5}$ concentrations of sidewalks. Previous studies have analyzed the relationship between canopy volume fraction (CVF) and $PM_{2.5}$ pollution (Karttunen et al., 2020; Hu and Ma, 2021), but CVF does not conclude the proportion of hedge volume within the street canyon (Gromke and Blocken, 2015). Therefore, GVR could better represent the greening characteristics of multilayer plant composites than CVF during this investigation. Unlike the traditional 2D evaluation indicator, GPR is a 3D indicator based on LAD, which is defined as the ratio of the total leaf area of all kinds of vegetation on the site to the study area. The higher the ratio of GPR is, the better the ecological benefits (Ong, 2003). However, the more complex the vegetation structure, the higher the 3D greening quantity, and the greater the greening quantity is, the more unfavorable the diffusion of pollutants in street canyons. VVF and SVF are novel indicators related to the green quantity, which measure the green volume and street spatial structure from the human visual perspective, which is obtained through field measurement and big data of street view images (Miao et al., 2020). Therefore, there are differences in the green volume observed at different sites. Both PVVF and PSVF are observations obtained on the sidewalk near the street vegetation, and thus have higher correlations with ARDC compared to CVVF and CSVF. This study explored the correlations among green quantity factors and SVF with ARDC, with the aim of evaluating the influence of vegetation configuration on concentration from a 3D perspective, and providing an optimal green quantity range for landscape or tree planting processes, thereby enhancing the practicality and applicability of the study. The above results indicate that GVR and GPR are important parameters for characterizing the impact of street patterns on the air quality in street canyons from a 3D perspective. GVR below 0.01 and GPR below 0.37 could be suggested to

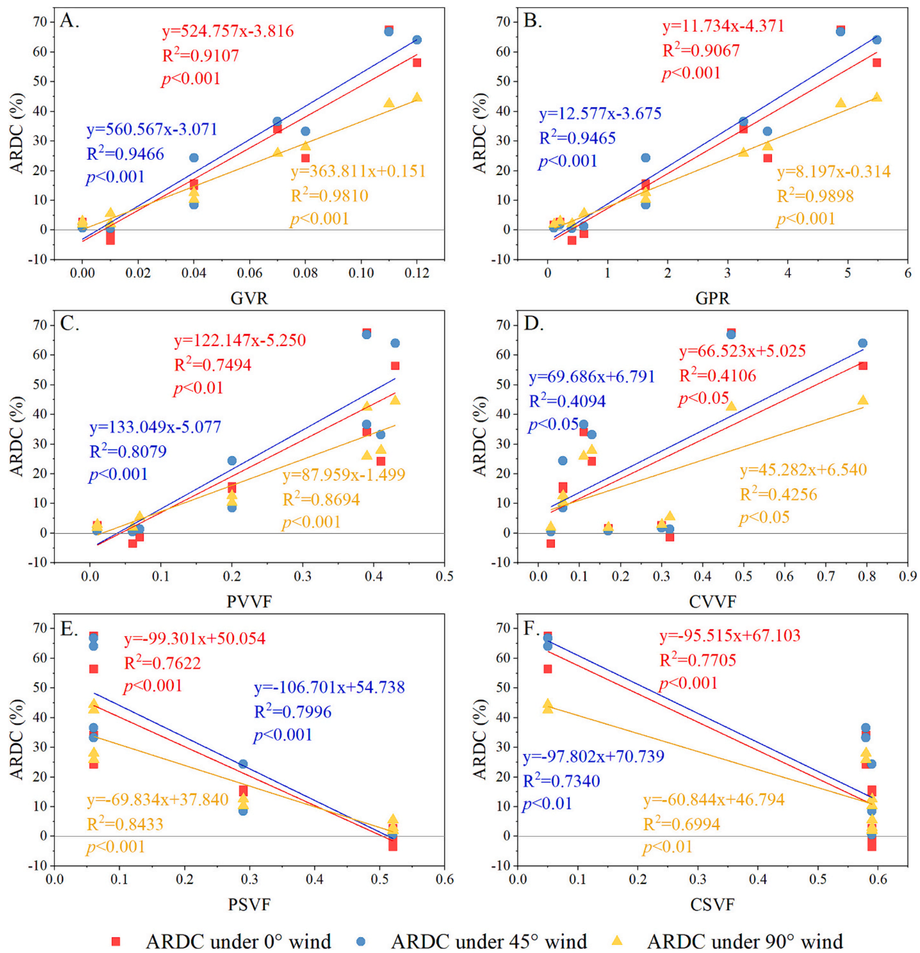

Fig. 10. Correlation analysis between green quantity factors and ARDC. (A) GVR; (B) GPR; (C) PVVF; (D) CVVF; (E) PSVF and (F) CSVF.

improve the dispersion of $PM_{2.5}$ in street canyons.

4.4. Limitations and suggestions

This investigation explored the effect of green patterns on $PM_{2.5}$ dispersion in street canyons under three wind directions during the summer period. The morphology and density of vegetation have different characteristics in different seasons (Wu et al., 2021), such as LAD will change, which affects the vegetation effect on local air pollutants. Additionally, the reduction effect of green patterns on PM is also related to the geometric morphology of the street. This investigation only considered the idealized street ($H/W = 1.0$) and found that the results were different from shallow street ($H/W = 0.5$) (Jeong et al., 2023), thus further research should explore the integrated impact of green patterns, street geometric morphology and meteorological factors in different seasons. In addition, the metrological factors (such as wind speed and temperature) should also be validated in the future research and scaled outdoor experiments are good choice (Hang and Chen, 2022; Bai et al., 2023). Future research could also explore various pollutant mode and chemical processes, taking into account the emissions from trees and hedges (Wang et al., 2023; Maison et al., 2024).

The green pattern setting (including green scenarios and related growth parameters of arbor and hedge) was based on a previous investigation, and all grid values of each sidewalk were extracted to explore the influence of green pattern and wind direction. These conclusions could be extended to regions with similar climate and vegetation (Li et al., 2023). The above theory aims to more accurately reveal the $PM_{2.5}$ dispersion mechanism within street canyons, and provides practical and feasible suggestions for the construction or management of street green patterns. Although this investigation shows that some green patterns may worsen street air quality, especially two rows of trees and three rows of trees. It should be noted that the design of street vegetation should take into account not only the air purification function of vegetation, but also the other design purposes (e.g., microclimate improvement or aesthetic services). Green pattern design should be performed to achieve a trade-off solution between the various ecosystem services and disservices that are provided. For example, unilateral-tree on the windward side or two rows of hedges may be the optimal vegetation pattern proposed for city planner or landscape designers.

5. Conclusions

This study investigates the effect of different greening patterns on $PM_{2.5}$ dispersion within a three-dimensional street canyon under varying wind directions. The key findings are as follows:

- The leeward side exhibits higher $PM_{2.5}$ concentrations than windward side under perpendicular and oblique wind conditions. Under parallel wind condition, the horizontal distribution of $PM_{2.5}$ concentration is almost symmetrical along the central axis of the street canyon. Furthermore, the order of $PM_{2.5}$ concentration for the same green scenario is perpendicular wind > oblique wind > parallel wind.
- The concentration of $PM_{2.5}$ gradually decreases with increasing vertical height. However, the decrease in $PM_{2.5}$ concentration in vertical space varies with wind direction and spatial location.

- The arbor-hedge vegetation structure has the highest total vegetation deposition due to more leaf area, and hedges have better deposition amounts per unit volume due to proximity to emission sources.
- The $PM_{2.5}$ concentration on each side increases with the number of tree rows, i.e., three rows of trees > two rows of trees > one row of trees. The $PM_{2.5}$ concentration on each side shows no significant change with an increase in the number of hedge rows, while there is a slight increase in $PM_{2.5}$ concentration with increasing hedge height.
- Wind direction and planting patterns jointly affect the dispersal mechanism of $PM_{2.5}$ within the canyon. Unilateral trees on the windward side or two rows of hedges may represent an optimal vegetation pattern, considering the trade-offs with other ecosystem services.
- ARDC was significantly positively correlated ($p < 0.01$) with GVR, GPR, PVVF, and CVVF, and significantly negatively correlated with PSVF and CSVF.

The above results could provide a practical reference for greenbelt configuration selection or optimization within street canyons in order to reduce human exposure to $PM_{2.5}$ and associated health risks.

CRediT authorship contribution statement

Xiaoping Chen: Writing – review & editing, Writing – original draft, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Jinyu He:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis. **Meng Han:** Software, Methodology. **Xuan Li:** Writing – review & editing, Investigation. **Ruofan Xu:** Visualization, Validation. **Hang Ma:** Writing – review & editing, Software. **Xiaoshuang Wang:** Writing – review & editing. **Xiaogang Wu:** Writing – review & editing. **Prashant Kumar:** Writing – review & editing, Methodology.

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.

Data availability

Data will be made available on request.

Acknowledgements

This research was sponsored by the National Natural Science Foundation of China (No. 32001369) and the Postgraduate Education Innovation Project in Shanxi Province (2022Y324, 2023KY325). PK acknowledges the funding support received from the UKRI (EPSRC, NERC, AHRC) funded RECLAIM Network Plus (EP/W034034/1) and the NERC-funded Green Cities (NE/X002799/1), and the EPSRC-funded INHALE (EP/T003189/1) projects. In addition, the authors wish to thank the reviewers for their valuable comments that further improved this paper.

Appendix A

Table A1
Simulation parameters of validation experiment.

Type	Name	Value
Location	Position	Taiyuan (37.87°N, 112.56°E)
Date and time	Start date	July 21, 2022
	Start time	07:00 AM
Meteorology	Wind direction	161.16°
	Wind speed	1.24 m s^{-1}
	Air temperature	Hourly average air temperature
	Relative humidity	Hourly average relative humidity
Model geometry	Dimension (x, y, z grids)	100 * 60 * 40
	Size of grid	2 m * 2 m * 3 m
	Nesting grids	10
Vegetation	Plant species	*Sophora japonica*
	Height	8.0 m
	Crown diameter	7.0 m
	LAD	1.0 m^2 m^{-3}
Pollutant	Type	$PM_{2.5}$
	Height	0.3 m
	Source geometry	Line
	Emission rate	Hourly average emission rate

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.176044.

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