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Study on the Impact of Winter Street Canyon Greening Mode on Nitrogen Oxide Diffusion Based on Numerical Simulation

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Abstract

This study uses ENVI-met numerical simulation software to analyze the effects of three typical greening patterns (single trees, trees + hedges, and trees + ground cover) on the dispersion of nitrogen oxides (NOx) in a street canyon in Lin'an District, Hangzhou, during winter parallel wind conditions. By simulating the distribution of NOx concentration at the height of the human respiratory zone under various greening modes, it was found that a single tree mode forms a significant high concentration pollution zone in the downwind area; The average NOx concentration of the tree+ground cover model is the highest, indicating that ground cover plants have a significant hindering effect on air flow; The combination of trees and hedgerows showed the lowest average NOx concentration, indicating that hedgerows have a significant effect in blocking pollutant diffusion and improving air flow. Research has shown that reasonable greening configuration plays an important role in improving air quality in street canyons, among which hedgerows have a better control effect on pollutant diffusion than ground cover plants. The results provide scientific basis for the greening design of street canyons in hot summer and cold winter areas, which helps to improve the air quality inside the street canyons, especially in ensuring pedestrian health, and has practical significance. Future research can further explore the impact of seasonal changes and wind speed on different greening modes, in order to optimize greening strategies and air pollution control plans.

Keywords

Street Canyon; Greening mode; Nitrogen oxides; Air quality.

1. INTRODUCTION

With the increasing popularity of electric vehicles, the sources of urban transportation emissions are undergoing changes. Although the emissions of pollutants from traditional fuel vehicles have decreased, traffic emissions remain an important factor in urban air pollution. Transportation emissions have surpassed industrial emissions and become the main source of urban air pollution. Due to the dense arrangement of buildings on both sides of street canyons in cities, air circulation is restricted, resulting in pollutants in motor vehicle exhaust, especially nitrogen oxides (NOx), being difficult to effectively diffuse in narrow spaces, seriously affecting air quality. In summer, strong sunlight promotes photochemical reactions between NOx and volatile organic compounds (VOCs), generating ozone (O3) and causing ozone pollution. In winter, the phenomenon of low temperature and inversion causes pollutants to remain in the streets and valleys for a long time, slowing down the diffusion rate and leading to a significant increase in NOx concentration [5]. The lower wind speed further weakens air flow, causing pollutants to accumulate near the streets, especially during peak morning and evening traffic periods. The air quality deteriorates sharply, posing a serious threat to the health of pedestrians,

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cyclists, and children at low altitudes in the breathing zone. Therefore, it is crucial to solve the problem of motor vehicle exhaust pollution in winter streets and valleys.

Current research indicates that the impact of meteorological and environmental factors on pollutant dispersion in street canyons has been extensively studied [7-9], but there has been relatively little attention paid to the role of greening patterns. Street trees can purify the air through photosynthesis, and their shading and cooling effects can improve microclimate and alleviate urban heat island effects. However, roadside trees can also affect air flow, producing a dual effect [11]. Previous studies have mainly focused on the impact of individual vegetation morphology, such as tree leaf area, crown width, and lower branch height, on air circulation and pollutant dispersion [12]. Qin et al.'s simulation study found that tree height, crown width, and canopy volume are the main factors affecting the efficiency of particulate matter reduction at pedestrian heights in street canyons [13]. Salmond et al. found through on-site monitoring that pollutants generated by vehicles are prone to accumulate around the canopy of trees and are difficult to diffuse. The height of the canopy has a significant impact on the diffusion of pollutants [14]. After summarizing the literature, Abhjith suggested avoiding the use of excessively tall trees to prevent further deterioration of air quality in street canyons, and advocated the use of low hedgerows [15]. However, most studies still focus on particulate matter (PM2.5, PM10) [16], and there is a relative lack of systematic research on gaseous pollutants such as NOx.

Lin'an District of Hangzhou City is located in a subtropical climate zone with hot summers and cold winters. By promoting street and valley greening construction, especially the planting of roadside trees, not only has the urban landscape been improved, but also the thermal comfort and high temperature environment have been significantly optimized. However, overly dense roadside trees may hinder air circulation, especially in winter, and have a negative impact on air quality [17]. Therefore, a reasonable vegetation configuration is crucial to achieve the dual goals of improving the microclimate of the street canyon and maintaining good air circulation.

Therefore, this study used Envi-met numerical simulation software to simulate the effects of three different roadside tree greening modes (single tree, tree+hedge, tree+ground cover) on the diffusion of nitrogen oxides in street canyons under parallel wind conditions in winter. By analyzing and comparing the diffusion regulation mechanisms of nitrogen oxides under different greening modes, evaluating their impact on the concentration of nitrogen oxides at pedestrian heights on sidewalks, and providing scientific basis for green management and design of streets and valleys in hot summer and cold winter areas.

2. MATERIALS AND METHODS

2.1. Basic Process

This study adopts a combination of field research and simulation modeling. Firstly, the greening status of streets and valleys in Lin'an District, Hangzhou was investigated, and three representative greening modes were selected. Based on the research results, corresponding simulation environment parameters were set, and Envi-met simulation software was used to model different scenarios. By simulating the results of representative time periods, conducting data analysis, and exploring the impact of various greening modes on the environment. The basic process of the research is shown in Figure 1.

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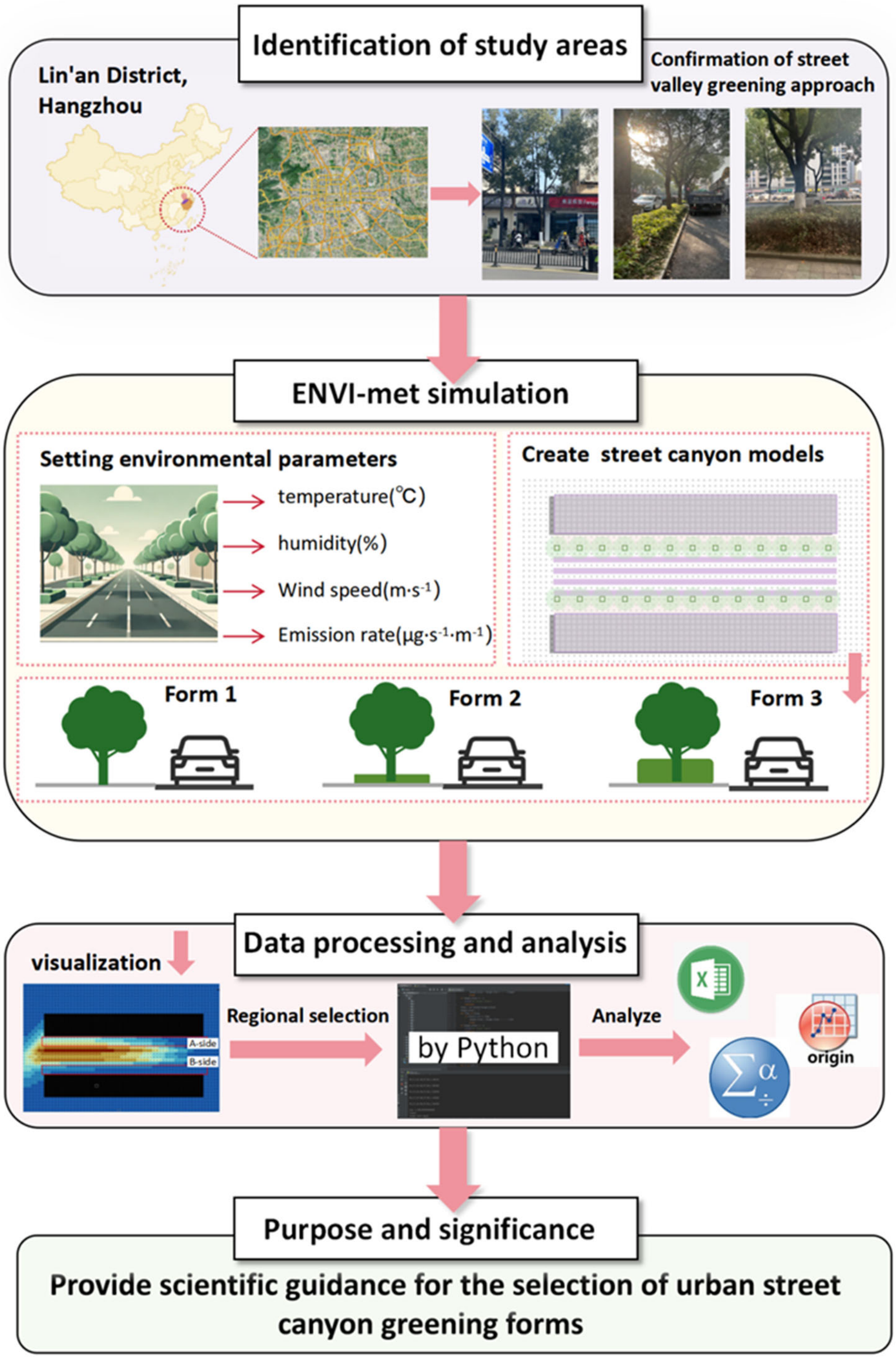

Figure 1. Basic flowchart

2.2. Introduction to Envi-met

Envi-met is a 3D microclimate simulation software developed by German environmental scientist Dr. Michael Bruse and his team, specifically designed to study the complex interactions between buildings, vegetation, and atmosphere in urban environments (Figure 2). This software is based on computational fluid dynamics (CFD) and thermodynamic models, and can accurately simulate the aerodynamics, heat transfer, and material diffusion processes in urban areas. It is widely used in urban planning, architectural design, and environmental research [18].

In terms of pollutant diffusion research, Envi-met has advanced simulation capabilities that can dynamically simulate the diffusion paths of atmospheric pollutants such as particulate matter (PM2.5) and nitrogen dioxide by combining fine meteorological data (such as wind

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speed, wind direction, temperature, humidity) with urban terrain and building structures. It accurately reflects the obstructive or guiding effects of buildings, block structures, and green spaces on airflow through physical models, and predicts the spatiotemporal distribution of pollutants under different weather and time conditions. ENVI-met not only supports the analysis of individual pollution sources, but also integrates multiple pollution sources (such as transportation, industry, etc.) for comprehensive simulation, helping researchers evaluate the pollution level and air quality in different regions, providing scientific basis for optimizing urban layout and mitigating air pollution.

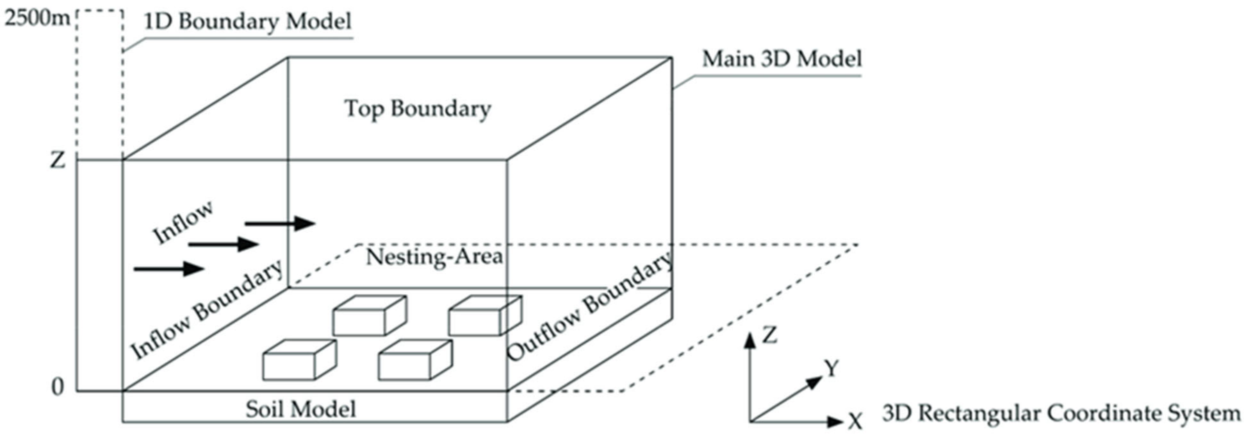

Figure 2. Schematic diagram of ENVI-met model structure

2.3. Simulation parameter settings

The selected location for environmental simulation is Lin'an District, Hangzhou City. Lin'an District is located in the western part of Zhejiang Province, with geographical coordinates of approximately 30.23 ° N and 119.72 ° E. It belongs to the subtropical monsoon climate zone, with distinct four seasons and an average annual temperature of 15-16 ° C. It also has abundant precipitation, with an annual precipitation of about 1500-1700 millimeters, concentrated in the rainy season and typhoon season (Figure 3). The forest coverage rate in Lin'an District is as high as 76%, with abundant green resources. The excellent ecological environment provides the city with a natural air quality regulation function, reducing the urban heat island effect and the accumulation of pollutants. However, with the development of the economy, the number of motor vehicles has been increasing year by year, especially private cars and trucks, which has brought certain pressure to the air quality in urban areas. Motor vehicle exhaust has become the main source of pollutants such as PM2.5 and nitrogen dioxide. Nevertheless, Lin'an District actively promotes the development of public transportation and new energy vehicles, and strengthens greening measures to reduce environmental burden. The annual average wind speed is about 2-3 meters per second, although the wind speed is not high, it is relatively stable. Due to the complex terrain, there are differences in air circulation in local areas of cities, and pollutants are prone to accumulate under low wind speeds, especially in summer and winter. Therefore, Lin'an District still needs to make continuous efforts in improving air circulation and promoting environmental policies to cope with the pressure of the growth of motor vehicles on the environment.

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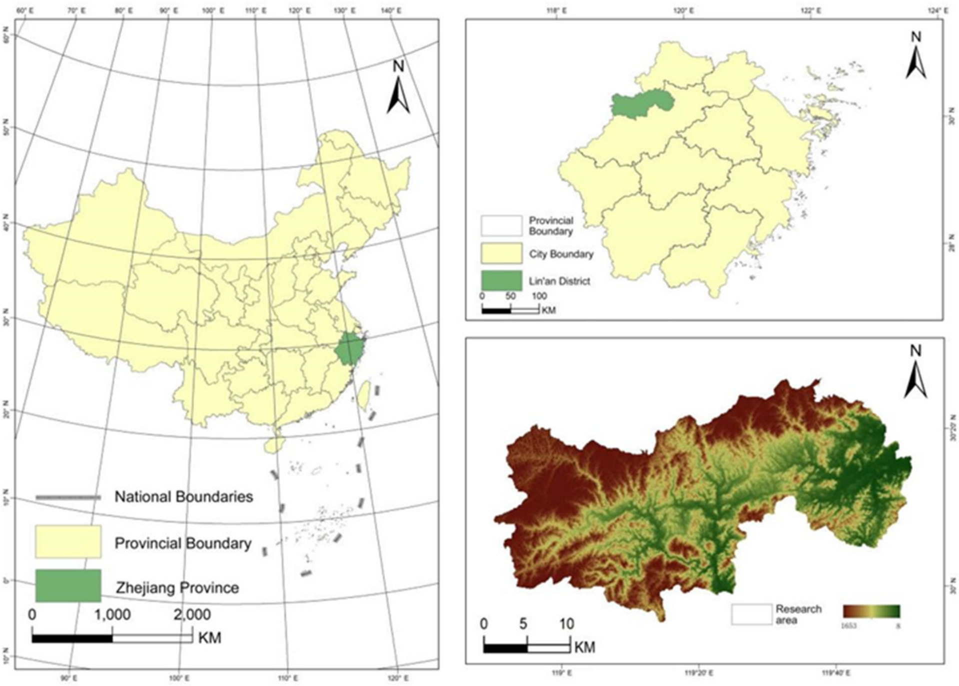

Figure 3. Geographical Location of Lin'an District

This study constructed an ideal street canyon model with a length of 100 meters and a height to width ratio of 1 based on actual measurements of the street through on-site research. The simulation environment is selected for the clear and windless winter of January 2024, with temperature set based on real-time data from the local meteorological station, ranging from -7 ℃ to 6 ℃, and humidity from 27% to 51%. The wind speed is taken as the typical outdoor wind speed in Lin'an District, Hangzhou during winter, with a value of 2m/s. To study the impact of vehicle traffic emissions on the environment, nitrogen oxides (represented as nitrogen dioxide) were selected as the pollution source. Considering the width of the road and the setting of four lanes in both directions, each lane is equipped with a pollution source with a discharge height of 0.3 meters.

By conducting actual statistics on the traffic flow of the research section, the pollutant emission rate v (unit: $\mu g \cdot s^{-1} \cdot m^{-1}$) is calculated using the formula v=E × q, where E is the unit emission of vehicles and q is the traffic flow. The calculation of emission rate is based on the Traffic Tool module of Envi-met software and is determined according to the traffic flow during different time periods. The simulation parameters are detailed in Table 1.

Table 1. Boundary condition settings for Envi-met model

Categorisation	Sports event	Parametric
Aeronautical	Minimum temperature/°C	-7
	Maximum temperature/°C	6
	Maximum humidity/%	51
	Minimum humidity/%	27
	Wind Direction/°	90
	Wind speed/(m·s-1)	2
Pollution source	Height/m	0.3
	length/m	100
	Emission rate/(μg·s-1·m-1)	126.7

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2.4. Case selection

Based on the results of field research, this simulation case determined the common greening modes of Lin'an street canyon and selected four representative greening combinations for study: single tree, tree+hedge, tree+ground cover, and no tree control mode (Figure 4). Among them, the representative tree species of Lin'an District, camphor tree, was selected as a single tree, with a planting spacing of 8 meters, a crown base height of 4 meters, and a crown width of 9 meters, all of which have strong representativeness. The height of the hedge is set to 1.1 meters, and the ground cover height is 0.2 meters. These dimensions also represent the common hedge and ground cover configurations in the street canyon, both planted in the distance between trees. These four representative green configurations will be used to analyze their impact on air quality and pollutant dispersion in street canyons.

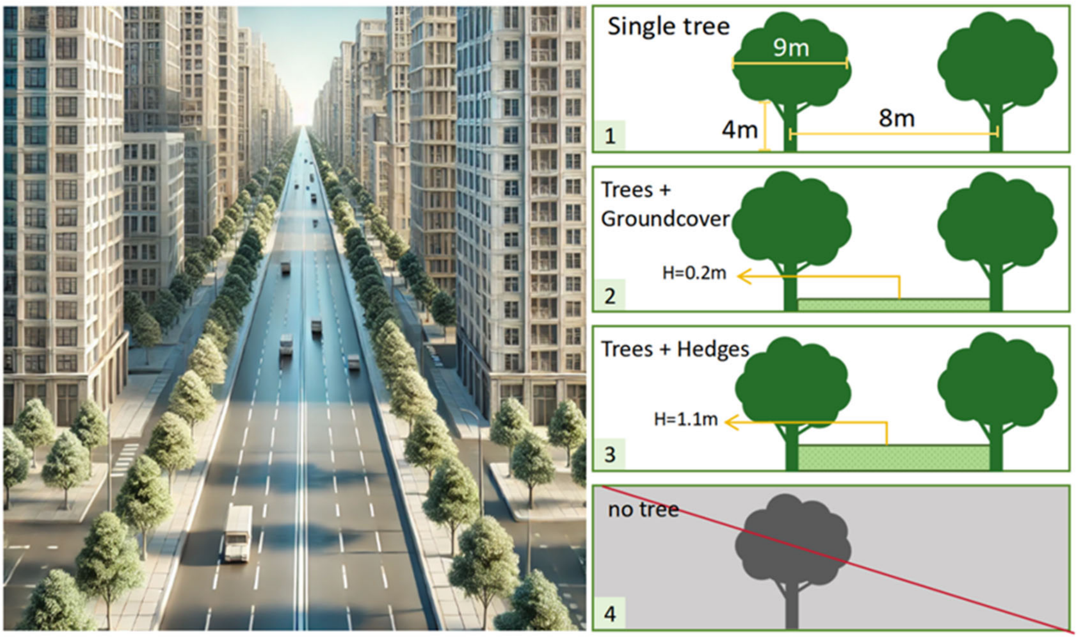

Figure 4. Display of Four Simulated Scenarios

2.5. Data Analysis

This study selected 17:00 during peak commuting hours as the time point for data analysis. The Leonardo module in Envi-met software was used to visualize the nitrogen oxide concentration (recorded as NO_2) and extract nitrogen dioxide concentration data on both sides of the pedestrian walkway in the street canyon for comparative analysis. NO_2 was selected as the recording object because it accounts for a high proportion of nitrogen oxides and has a significant impact on health.

To quantitatively analyze the impact of different green combinations on pedestrian height nitrogen oxide concentration, the relative concentration difference is used for evaluation, and the calculation formula is: $RDC=(C_{veg}-C_{ref}) \times 100\% \times C_{ref}^{-1}$, where RDC represents the effect of tree planting on nitrogen oxide concentration in the street canyon, C_{veg} represents the average concentration of pollutants in the scenario with plant planting, and C_{ref} represents the average concentration of pollutants in the control scenario without plant planting. Through this indicator, the scientific evaluation of the effect of greening on reducing the concentration of NO_2 in pedestrian breathing areas in street canyons can be achieved.

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3. RESULTS

The planar concentration field of NOx diffusion at a pedestrian height of 1.4 meters (Figure 5) shows the distribution of NOx diffusion in four different modes: single tree, tree+hedge, tree+ground cover, and treeless street canyon under parallel wind conditions. Compared with the control group of treeless street canyons, significant dark areas were observed in the three modes of single tree, tree+hedge, and tree+ground cover, indicating that these greening configurations have varying degrees of impact on the diffusion of NOx under parallel wind conditions.

In the single tree mode, a clear dark brown band appears in the central area of the street canyon, indicating that the NOx concentration is relatively high in the downwind direction of the trees. Although the trees do not obstruct the airflow, they still cause pollutants to form a long high concentration band in the downwind area. The dark area range and color of the tree+hedge mode are the widest and darkest, indicating that due to the obstruction effect of the hedge on air flow, NOx is difficult to diffuse in this mode, forming higher concentration peaks and leading to more severe accumulation of pollutants near the hedge. In the tree+ground cover model, dark areas are also more prominent, indicating that the vegetation on the ground has enhanced the turbulence effect. Although the diffusion range has been expanded, high concentration areas still exist, indicating limited inhibitory effect on pollutants.

In contrast, the treeless street canyon mode is mainly light colored, with a more uniform distribution and lower concentration of NOx, indicating that under parallel wind conditions without any greenery, the airflow can circulate quickly and smoothly, causing pollutants to quickly dilute and disperse, reducing the formation of high concentration areas. From this, it can be seen that all three greening modes produced dark and high concentration areas under parallel wind conditions, indicating the phenomenon of vegetation obstructing airflow and exacerbating pollutant accumulation.

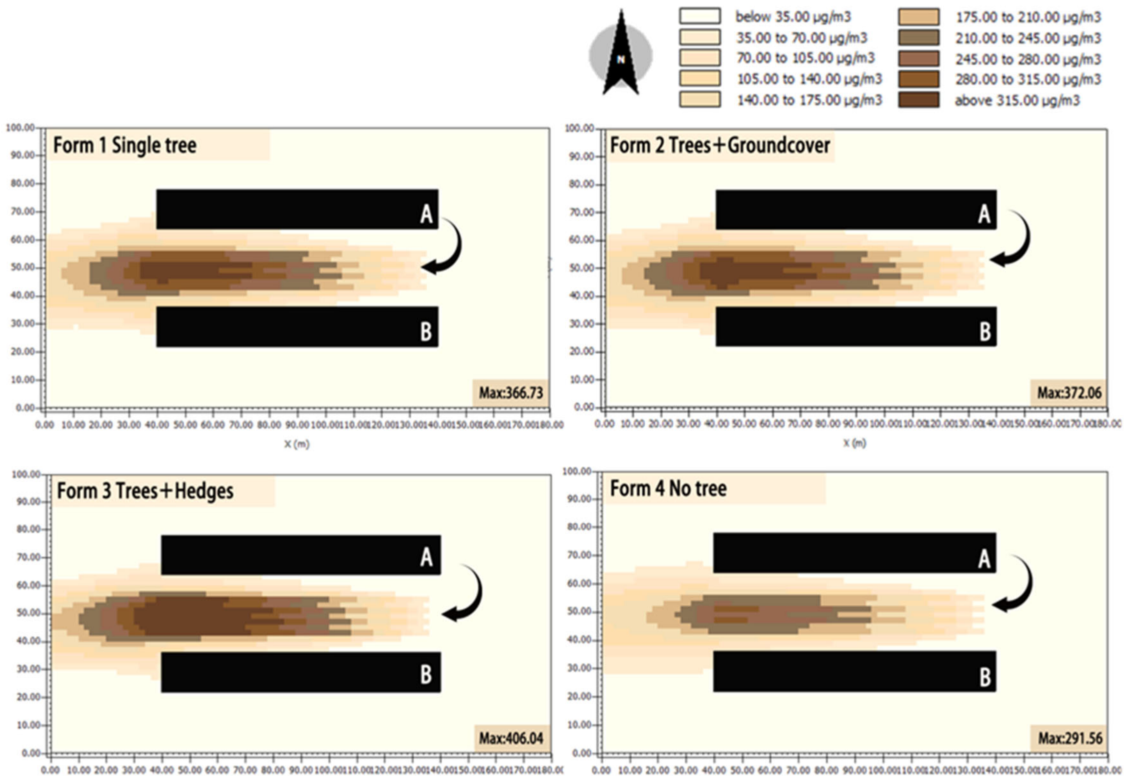

Figure 5. Plan of NOx concentration distribution at a pedestrian height of 1.4m under different greening modes

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Under parallel wind conditions, different greening modes have a significant impact on the average concentration of nitrogen oxides (NOx) in street canyons (Figure 6). Specifically, the treeless mode has the lowest average concentration of NOx, while the mode with increased greening configuration leads to an increase in concentration, indicating the hindering effect of vegetation on air flow and pollutant diffusion. The average NOx concentration in the treeless street canyon mode is 51.0 μ g/m ^{3}, which is the lowest among the four modes. This indicates that in the absence of vegetation barriers, air mobility is better, pollutants can quickly diffuse and dilute, and overall air quality is significantly improved. In this mode, there are no green plants obstructing the airflow in the street canyon, allowing pollutants to spread more evenly, resulting in better air quality for pedestrians. Although the treeless mode lacks the ecological benefits of greening, it has a significant effect in reducing pollutant concentrations.

In contrast, the average concentration of NOx in the single tree mode reached 70.1 μ g/m ^{3}, significantly higher than that in the treeless mode. This indicates that the presence of trees to some extent hinders the horizontal flow of air, causing pollutants to accumulate in the streets and valleys, especially in the downwind direction. The branches and leaves of trees block the airflow. Although a single tree mode helps provide basic greening benefits, it has a negative impact on air quality, inhibits the diffusion of pollutants, and increases the concentration of NOx.

Under the tree+ground cover mode, the average NOx concentration is the highest, reaching 71.1 μ g/m ^{3}. Although vegetation has increased the level of greenery, its effect on improving air flow is not significant. On the contrary, the increased vegetation on the ground impedes air flow, leading to more severe retention of pollutants and an increase in concentration. The increase of NOx concentration in this mode shows that ground cover plants have not effectively improved the air mobility in the street canyon, but have intensified the pollution accumulation in the downwind direction, which is the most adverse impact on air quality.

The average concentration of NOx in the tree+hedge mode is 65.1 μ g/m ^{3}, slightly lower than that in the single tree and tree+ground cover modes. Although the hedge creates obstacles to airflow to some extent, its low height still allows airflow to diffuse pollutants through the hedge area to a certain extent. In this mode, although the inhibitory effect of hedgerows on pollutants exists, their impact on air flow is slightly smaller compared to ground cover plants, resulting in a slight improvement in overall air quality.

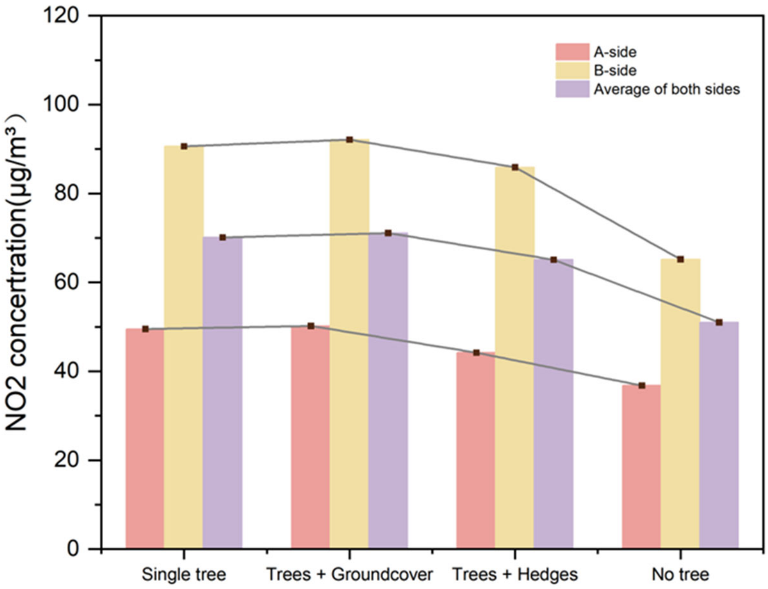

Figure 6. Comparison of pedestrian density on both sides of the street canyon at a height of 1.4m under different greening modes

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According to the relative concentration difference (RDC), different greening modes increased the concentration of nitrogen oxides (NOx) in the street canyon compared to the no tree control scenario. In the single tree mode, the average RDC is 36.73%, indicating a significant impact of this mode on the increase of NOx concentration; The average RDC of the tree+ground cover model is 38.82%, the highest among all models, indicating that ground cover plants further exacerbate pollutant accumulation, leading to a particularly significant increase in NOx concentration. In contrast, the average RDC of the tree+hedge mode is the lowest, only 25.93%. Although it still has a certain increase in NOx concentration, the increase is relatively small, indicating that the hedge has the least obstructive effect on air flow and the least NOx accumulation. Therefore, the tree+hedge model has the least impact on air quality while balancing greening benefits (Figure 7).

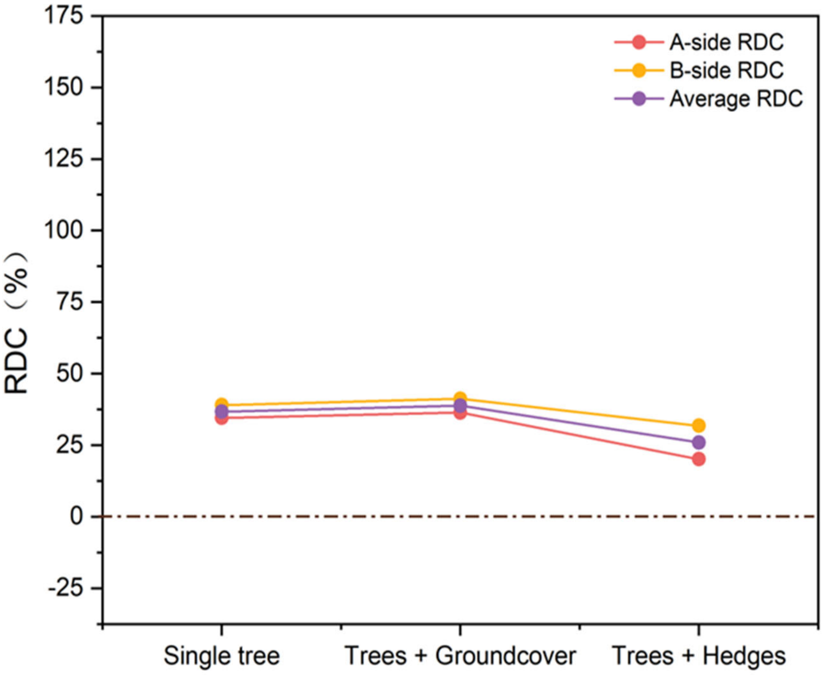

Figure 7. RDC on both sides of the 1.4m pedestrian height street canyon under different greening modes

According to the contour map of NO_2 concentration field and wind speed in the middle section of the street canyon (Figure 8), it can be seen that different greening modes have a significant impact on the distribution of NO_2 concentration and air flow in the street canyon. As shown in the figure, under the combination of trees and ground cover, the obstruction of air flow by ground cover plants on the surface is relatively small, but it reduces the wind speed near the ground, resulting in the accumulation of NO_2 concentration in the lower layers. The ground is mainly covered by vegetation, which cannot effectively block the spread of pollutants from the road to the sidewalk. Due to the presence of ground cover plants, the flow of air near the ground is slowed down, resulting in higher concentrations of NO_2 in low altitude areas, especially in areas where trees cannot directly affect.

Under the combination of hedgerows and ground cover, the height of the hedgerows is low and the structure is dense, effectively forming a barrier between the ground and the sidewalk. The wind speed contour line shows that the hedge blocks the air flow between the road and the sidewalk, limiting the lateral diffusion of NO_2. Due to the high leaf area index of hedgerows, they have a stronger retention effect on pollutants, further reducing the concentration of NO_2 in the

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lower areas. Although the blocking effect of ground cover plants is not strong, with the assistance of green hedges, the low-level air flow is further restricted, which helps to reduce the diffusion of NO_2 near sidewalks.

In contrast, the wind speed contour lines of a single tree model show relatively smooth airflow. The canopy of the tree is located at a higher level, which has a relatively small impact on the diffusion of ground pollutants. The air can freely circulate, allowing NO_2 to spread and accumulate over a large area near the sidewalk. Therefore, at pedestrian height, the concentration of NO_2 is lower in the hedge+ground cover mode, while it is more likely to form a high concentration accumulation area in the ground cover+tree mode.

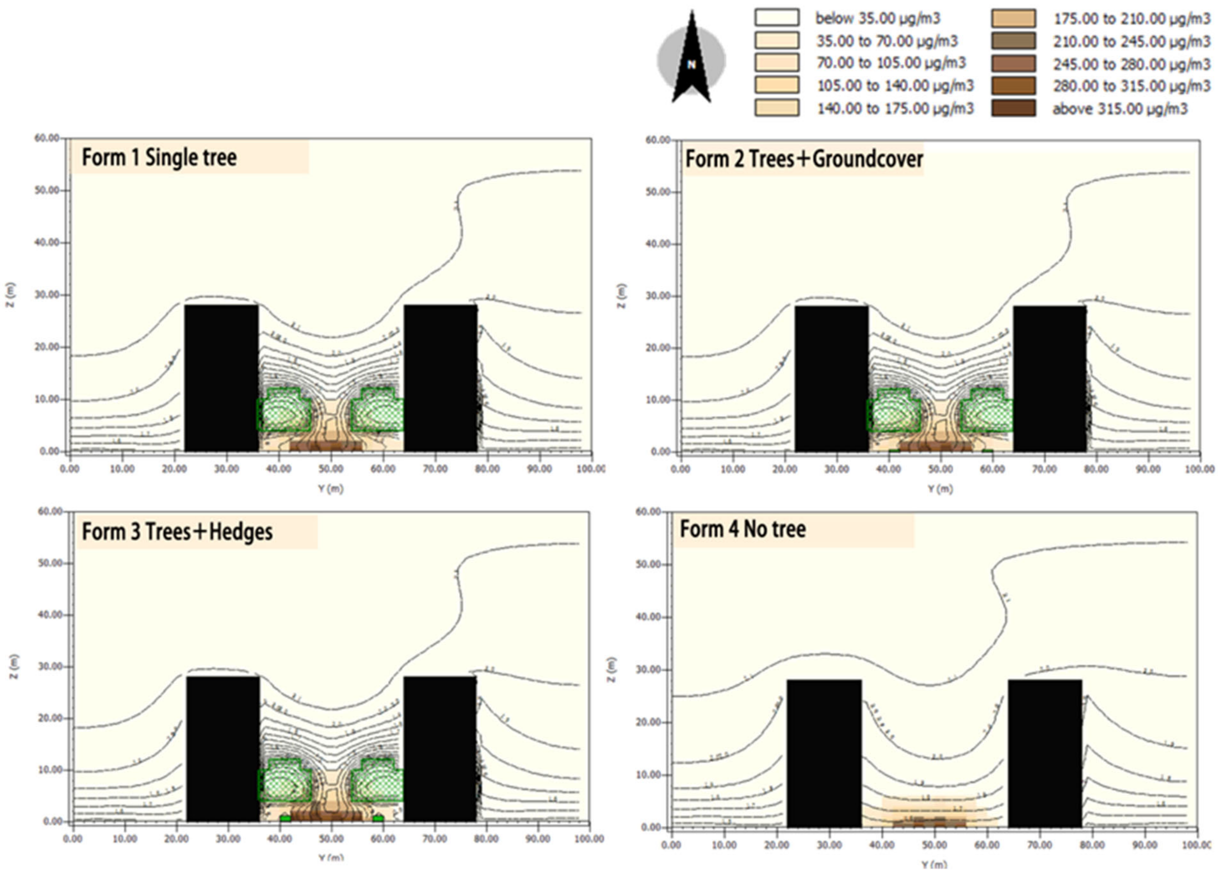

Figure 8. RDC on both sides of the 1.4m pedestrian height street canyon under different greening modes

4. DISCUSSION

This study indicates that different greening modes have a significant impact on NOx concentration and air flow in street canyons. In the single tree mode, the average concentration of NOx is higher than that in the treeless mode, which is related to the local obstruction effect of trees on airflow. Although trees contribute to high-level air flow, they have limited diffusion of low-level pollutants, leading to the accumulation of pollutants in ground areas. Corresponding to the higher concentration of the combination of trees and ground cover, ground cover plants mainly affect the airflow near the ground, failing to effectively prevent the diffusion of pollutants in the lower layers. Instead, due to their close proximity, they slow down the surface airflow and increase the retention of NOx in the lower layers.

Compared with previous studies, Abhjith et al. suggested that hedgerows have a smaller impact on air flow, and the tree+hedgerow model showed lower NOx concentrations [19]. Green hedgerows, with their dense structure, effectively block the spread of road pollutants and

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reduce interference from low-level air flow. This is consistent with the conclusion found by Salmond et al. that vegetation types and heights have an impact on pollutant dispersion [20]. The combination of hedge and ground cover not only has a good effect on retaining pollutants, but also has a relatively mild limiting effect on low-level airflow, which helps balance air circulation and pollution control.

The analysis of specific results shows that the combination of trees and ground cover has insufficient hindering effect on the diffusion of pollutants in the ground area, which leads to the accumulation of pollutants in the lower layers. According to the RDC value, this combination has the greatest impact on the increase of pollutant concentration, mainly because the coverage area of ground cover plants is limited and cannot effectively control the diffusion of upper air.

It can be inferred that in the case of low wind speed and easy accumulation of pollutants in winter, the single tree and tree+ground cover mode may exacerbate air quality problems, while the hedge configuration is more helpful in maintaining air circulation in the street canyon while controlling the spread of pollutants.

In summary, hedgerows have significant advantages in street and valley greening, especially in hot summer and cold winter areas, helping to balance greening benefits and air quality.

5. CONCLUSION

This study used Envi-met numerical simulation software to investigate the effects of three typical greening modes (single tree, tree+hedge, tree+ground cover) on nitrogen oxide (NOx) diffusion under parallel wind conditions in streets and valleys in Lin'an District, Hangzhou during winter. By simulating the NOx concentration field at a pedestrian height of 1.4 meters, the regulatory effect of different vegetation configurations on air pollution in street canyons was analyzed, providing a scientific basis for street canyon greening management and design.

The research results indicate that greening configuration significantly affects the diffusion and retention characteristics of NOx in street canyons. The single tree mode forms a significant high concentration pollution zone on the downwind side, with the tree+ground cover mode having the highest average concentration of NOx, while the tree+hedge mode has relatively less obstruction to air flow and the lowest average concentration. These results indicate that the effectiveness of trees and ground cover plants in improving air quality is relatively limited, especially under low wind speed conditions in winter, where improper vegetation configuration may exacerbate the retention of pollutants. Green hedgerows, due to their dense structure and low height characteristics, have shown good effectiveness in blocking the spread of road pollutants, helping to reduce the concentration of pollutants at pedestrian heights.

This study has significant practical implications. The air pollution in the streets and valleys directly affects the health of pedestrians, especially sensitive groups such as children and the elderly. In the process of urban development, reasonable design of street and valley greening can not only beautify the environment, but also improve air quality to a certain extent and ensure pedestrian health. Future research should further explore the impact of green combinations on pollutant diffusion under other seasons and wind speed conditions, and consider more types of vegetation configuration to optimize street canyon air quality management strategies. Through more detailed research, we can provide stronger support for urban greening policies, helping decision-makers maximize pedestrian health benefits while improving landscape effects.

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