

Delineating the Impact of Three-Dimensional Morphological Parameters of Street Trees on Air Pollution: A Numerical Investigation of CO Concentration in Xi'an, China

Zongzhou Zhu ^{1,*}, Dan Wang ¹, Dixuan Ma ², Chaoyi Ma ¹, Dongliang Wang ¹, Yimeng Feng ³, Yue Xia ⁴ and Weili Yang ^{1,*}

¹ School of Mechanics and Transportation Engineering, Northwestern Polytechnical University, No. 127 Youyi West Road, Xi'an 710072, China

² School of Human Settlements and Civil Engineering, Xi'an Jiaotong University, No. 28 Xianning West Road, Xi'an 710049, China

³ Department of Architecture (DA), University of Bologna, 40136 Bologna, Italy

⁴ Department of Architecture and Urban Studies (DASTU), Politecnico di Milano, 20133 Milan, Italy

* Correspondence: zhu0527@nwpu.edu.cn (Z.Z.); yangweili@nwpu.edu.cn (W.Y.); Tel.: +86-195-0292-9886 (Z.Z.); +86-131-8605-3901 (W.Y.)

How To Cite: Zhu, Z.; Wang, D.; Ma, D.; et al. Delineating the Impact of Three-Dimensional Morphological Parameters of Street Trees on Air Pollution: A Numerical Investigation of CO Concentration in Xi'an, China. *Urban and Building Science* **2026**, *2*(3), 5. <https://doi.org/10.53941/ubs.2026.100019>

Received: 26 March 2026

Revised: 8 July 2026

Accepted: 9 July 2026

Published: 21 July 2026

Abstract: This study aims to investigate the perturbation mechanisms of street tree morphological characteristics on the near-surface carbon monoxide (CO) concentration distribution at the micro-scale. Based on the L16(4⁵) orthogonal experimental design and numerical simulations, the impacts of four morphological parameters—tree height, branching height, crown spread, and canopy edge distance—on CO concentration were systematically quantified. Range and variance contribution analysis indicate that branching height is the absolute dominant factor governing CO dispersion with a contribution rate of 49.97%, which significantly promotes the dissipation of bottom-level pollutants by expanding the under-canopy clearance. Crown spread, with a contribution rate of 25.58%, exhibits a marginally significant positive correlation with CO concentration due to enhanced aerodynamic resistance, whereas the effect of tree height does not reach statistical significance. Furthermore, by eliminating redundant variables through stepwise regression analysis, a multivariate empirical prediction model for CO concentration ($R^2 = 0.77$) was established, incorporating branching height, crown spread, and canopy edge distance as independent variables. This study reveals the decisive role of under-canopy spatial permeability in regulating the microclimate environment, and provides a solid quantitative basis for the topological optimization of urban green spaces targeting low pollutant retention and the precise selection of street trees.

Keywords: pollutant dispersion; street greenery; tree morphology; orthogonal experiment

1. Introduction

With the acceleration of urbanization in China and the continuous rise in the number of motor vehicles, road traffic has become one of the primary sources of urban air pollution. Economic growth has driven motor vehicles to become the main mode of transportation for urban residents, further exacerbating the impact of road pollution on the urban environment. According to forecasts by the Organisation for Economic Co-operation and



Development (OECD), if no effective intervention measures are taken, air pollution is expected to become the leading cause of environment-related deaths by 2050 [1]. As of 2025, the national motor vehicle fleet had surpassed 450 million vehicles, with 559 million licensed drivers [2]. Although new energy vehicles have developed rapidly in recent years, traditional fossil fuel-powered vehicles remain the mainstay of urban transportation. Pollutants emitted by motor vehicles, such as carbon monoxide (CO), fine particulate matter (PM_{2.5}), and nitrogen oxides (NO_x), tend to accumulate in street canyons, and CO emissions from vehicles are the primary source of urban CO. As a fundamental unit of urban spatial structure, street canyons serve as one of the primary spaces for residents' daily outdoor activities. The accumulation of air pollutants in these spaces can severely impact pedestrian respiratory health, and the geometric configuration of streets can significantly alter wind field structures and pollutant dispersion pathways [3]. Therefore, in-depth investigation of pollutant dispersion mechanisms within street canyons, particularly the influence of greenery, is of great significance for improving urban air quality and safeguarding public health.

Currently, research methods for pollutant dispersion in street canyons primarily include field monitoring, wind tunnel experiments, and computational fluid dynamics (CFD) numerical simulations. Field monitoring can reflect pollutant distribution under real-world conditions, but due to limitations in spatiotemporal resolution and environmental controllability, it is difficult to investigate the global spatial distribution of pollutants and the precise effects of specific influencing factors on pollution [4,5]; while wind tunnel experiments allow for variable control, they are costly and struggle to replicate complex urban topographies [6]. CFD simulations, with their flexibility, reproducibility, and low-cost advantages, have become the mainstream tool for studying pollutant dispersion at the street scale [7,8]. For example, Gong et al. used a CFD model validated by wind tunnel experiments to investigate the impact of asymmetric building layouts on pollutant dispersion in street canyons, finding that adjusting building heights to 2H and 3H significantly improved ventilation efficiency [9]. Cui et al. analyzed the spatiotemporal distribution characteristics of pollutants such as CO and PM_{2.5} in street canyons using mobile observation technology, revealing the correlation between meteorological factors and pollutant concentrations [10]. Ahmadi et al. employed a hybrid RANS-LES method to perform high-precision simulations of pollutant dispersion in urban street canyons, demonstrating the advantages of CFD technology in characterizing complex turbulence and dispersion processes [11].

Existing studies have largely focused on the effects of street geometric characteristics—such as aspect ratio and symmetry, intersection types, and building layouts—on pollutant dispersion. For example, Luo et al. [6] found through OpenFOAM simulations that three-way intersections exhibit the poorest ventilation efficiency, and that an increased street aspect ratio further inhibits pollutant dispersion. Zhou et al. noted that in symmetric street canyons, an increased aspect ratio leads to a more complex flow field structure and alters pollutant dispersion pathways; in asymmetric street canyons, the leeward side of ascending canyons is prone to pollutant accumulation [12]. Zhao et al. compared six types of building block configurations and found that descending blocks had the best ventilation, while level blocks had the worst [7]; furthermore, differences in building heights can enhance vortex structures within the canyon, promoting pollutant dispersion. Liu et al. further investigated the impact of roadway layout on pollutant dispersion in street canyons, finding that air quality in shallow canyons was generally better than in deep canyons, and that the position of the roadway significantly influenced the uniformity of pollutant distribution [13]. These studies reveal the significant impact of street morphology on pollutant dispersion, providing a theoretical basis for street design. Field studies by Miao et al. similarly confirm that morphological characteristics of street canyons, such as the height-to-width ratio and length-to-width ratio, have a significant impact on the concentration of particulate matter at pedestrian height [14], collectively offering important references for urban planning and street design optimized for ventilation performance.

However, while street greening serves as a key means of regulating the urban micro-environment, its mechanisms of influence on pollutant dispersion have not yet been fully elucidated. Vegetation can affect pollutant distribution through canopy interception, deposition, and alterations to the flow field; however, its effects are dual-natured: on the one hand, vegetation can adsorb particulate matter and reduce local concentrations; on the other hand, dense canopies may impede ventilation, leading to the accumulation of pollutants at pedestrian height [15,16]. Hu et al. found through ENVI-met simulations that street greening can increase PM_{2.5} concentrations on pedestrian paths by 9.34–99.70% [15]. A study on shrub vegetation indicated that in shallow street canyons, the presence of shrubs may increase pollutant concentrations, with higher concentrations associated with greater shrub height and density [17]. Zhao et al. further noted that excessive canopy closure and enclosure of green spaces can inhibit pollutant dispersion, whereas increasing green space area and average height facilitates pollutant dilution [18]. Karttunen et al. used large-eddy simulation to investigate the impact of street tree layout on pedestrian-level aerosol concentrations and explored possibilities for optimizing the layout [19]. These studies indicate that there is a complex trade-off between greening structures and pollutant dispersion, which urgently requires systematic quantification;

furthermore, there is a complex nonlinear relationship between greening structures and pollutant dispersion, necessitating systematic quantitative analysis.

Although previous studies have examined the effects of green coverage, vegetation types, and layout on pollutant dispersion, systematic, comprehensive research on the three-dimensional morphological parameters of street trees—such as tree height, crown spread, branching height, and canopy edge distance (planting spacing)—remains limited. As the primary component of street greening, the three-dimensional parameters of street trees directly influence the interaction between canopy structure and wind fields, thereby altering pollutant dispersion pathways and pedestrian exposure levels. For example, excessively large canopies or dense planting may create a “micro-canal effect”, inhibiting near-surface ventilation [20]; conversely, appropriate branching heights and tree spacing may facilitate airflow penetration and enhance vertical pollutant dispersion. Currently, most studies simplify vegetation as a homogeneous medium and investigate the impact of only one or a few tree-related factors on pollutant dispersion, failing to fully account for the differences in the actual three-dimensional morphology of trees and their coupling effects with various parameters [19].

Therefore, this study focuses on typical summer meteorological conditions and urban roads in Xi'an, selecting CO as a representative pollutant from vehicle exhaust. By constructing an ENVI-met numerical model and employing a factorial design, the study systematically investigates the synergistic effects of four three-dimensional morphological parameters—street tree height, branching height, crown spread, and canopy edge distance—on CO diffusion within street canyons. The study aims to: (1) clarify the extent to which the three-dimensional parameters of street trees influence CO diffusion; (2) quantify the main effects of each morphological parameter and their interactions; (3) propose a prediction model and street tree planting strategy optimized for pollutant diffusion, providing a scientific basis for the maintenance and renewal of urban street greening, and contributing to the creation of a healthy and sustainable street living environment.

2. Materials and Methods

This study selected roads within the old city area inside Xi'an's city walls as the case study, primarily based on the following considerations: First, streets in the old city typically exhibit a classic street canyon morphology, where poor ventilation causes pollutants such as CO from vehicle emissions to easily accumulate near the ground, making the pollution problem particularly prominent; second, streets in the old city support high-density pedestrian and bicycle traffic as well as daily resident activities, resulting in extremely high health risks from pollution exposure; more importantly, the old city faces the practical dilemma of an extreme scarcity of available green space, making traditional greening strategies difficult to implement. Therefore, exploring how to facilitate microclimate circulation and promote the dispersion of pollutants by finely adjusting the three-dimensional form of street trees, without altering the existing two-dimensional land use layout, holds urgent practical significance and provides guidance for current urban renewal efforts focused on micro-renovation. This study establishes a closed-loop scientific research methodology system ranging from variable dimensionality reduction and screening to quantitative predictive modeling, specifically comprising the following four aspects. The specific technical route is shown in Figure 1.

2.1. Experimental Design

To overcome the “curse of dimensionality” and high computational costs associated with full-factorial experiments involving multiple factors and levels, a design of experiments (DOE) was conducted around four factors with four levels each: tree height (14/16/18/20 m), branching height (4/5/6/7 m), crown spread (6/7/8/9 m), and distance to the canopy edge (0/1/2/3 m). An L16(4⁵) orthogonal array was used to arrange 16 experimental groups, with each group corresponding to a specific parameter combination (Table 1). This method leverages the mathematical property of spatial uniformity to capture the core response patterns of the global parameter space with a minimal sample size.

Table 1. Factors, Levels, and Orthogonal Experimental Groups.

Experiment Group Factors and Levels	4-Factor			
	Tree Height (m)	Branching Height (m)	Canopy Spread (m)	Canopy Edge Distance (m)
	14/16/18/20 (m)	4/5/6/7 (m)	6/7/8/9 (m)	0/1/2/3 (m)
1	14	4	6	0
2	14	5	7	1

Table 1. Cont.

Experiment Group Factors and Levels	4-Factor			
	Tree Height (m)	Branching Height (m)	Canopy Spread (m)	Canopy Edge Distance (m)
	4 Levels 14/16/18/20 (m)	4/5/6/7 (m)	6/7/8/9 (m)	0/1/2/3 (m)
3	14	6	8	2
4	14	7	9	3
5	16	4	7	2
6	16	5	6	3
7	16	6	9	0
8	16	7	8	1
9	18	4	8	3
10	18	5	9	2
11	18	6	6	1
12	18	7	7	0
13	20	4	9	1
14	20	5	8	0
15	20	6	7	3
16	20	7	6	2

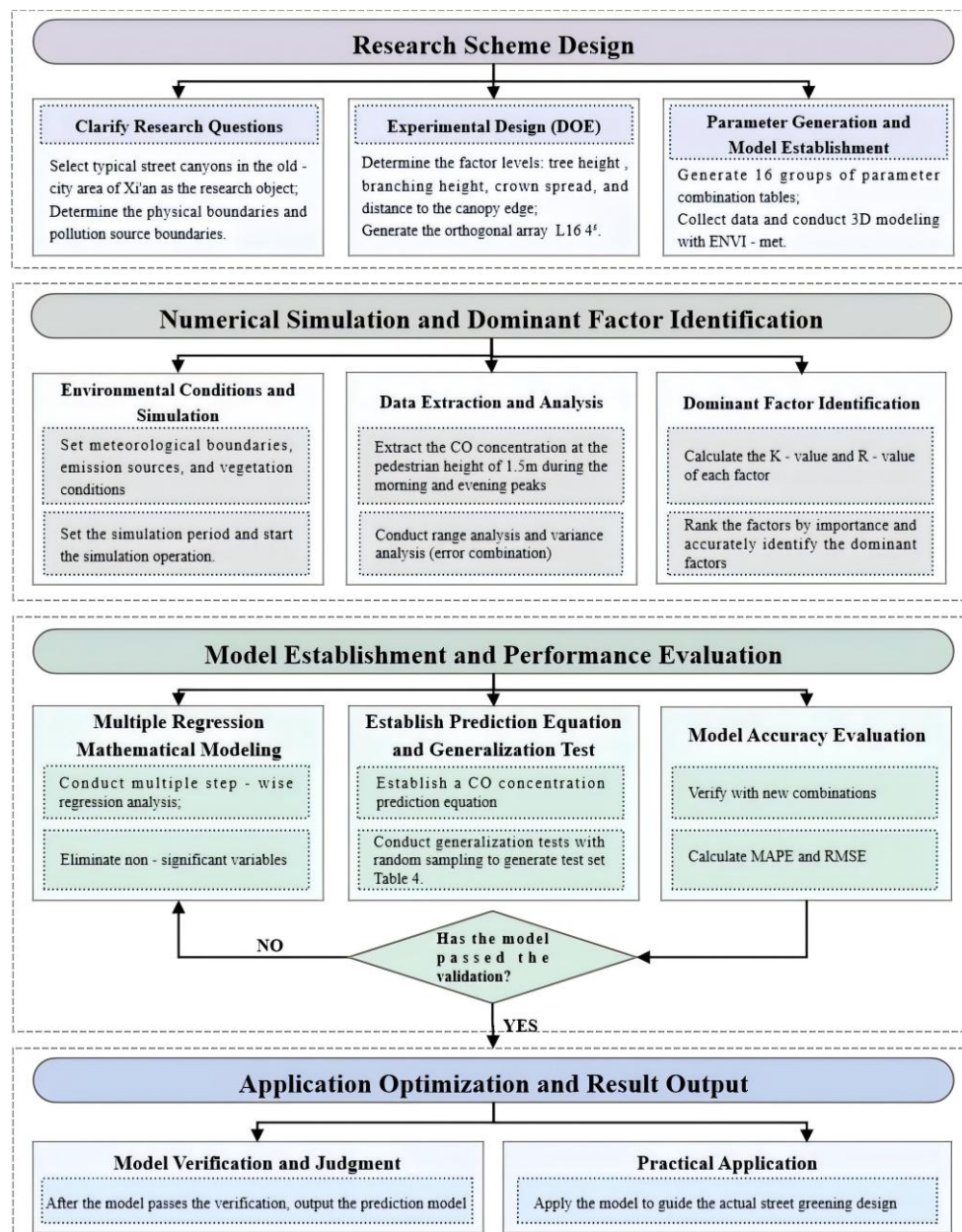


Figure 1. Technical Route.

2.2. Numerical Simulation and Data Acquisition

Based on a survey of residential street spaces in Xi'an's old city, common street dimensions were selected as the basis for the street's physical boundaries: a street width of 18 m, with 7-story residential buildings 21 m high on both sides. The vegetation was set to the most common tree in Xi'an, the Chinese scholar tree (*Sophora japonica*). The morphological parameters—tree height, branching height, crown spread, and canopy edge distance—are shown in Figure 2. Using ENVI-met software, a three-dimensional numerical model was constructed for the study, and numerical simulations were conducted. This software has the capability to simulate atmospheric processes, radiation transfer, vegetation physiology, and pollutant dispersion within the urban canopy at high resolution. The model settings are listed in Table 2. The simulation was set for 3 August 2024, a typical summer day in Xi'an. Meteorological parameters—including temperature, humidity, wind speed, and wind direction—were sourced from the Jinghe National Meteorological Station (Table 3). The number of motor vehicles was set in accordance with the “Planning Standards for Urban Integrated Transportation Systems (GB/T 51328-2018)”, for urban secondary arterials, the bidirectional traffic volume during peak hours is set at its upper limit of 2000 pcu/h. The vehicle exhaust emissions were based on the “Emission Limits and Measurement Methods for Light-Duty Vehicles (China Stage VI b)”; the CO emission factor for motor vehicles is quantified as 50 mg/km. It is worth noting that, to prevent model instability induced by fluctuations in wind speed and direction, the daily mean value was adopted for wind speed, while the daily prevailing wind direction was employed for wind direction. To ensure the software was fully warmed up and to guarantee the accuracy of the simulation results, the simulation period began at 17:00 on 2 August and continued until 23:00 on 3 August. The study selected data from two time periods: 3 August, 7:00–9:00 and 18:00–20:00, when urban traffic and pedestrian congestion were at their peak, and CO concentrations had the most direct and intense impact on pedestrians, the subjects of analysis. In line with previous research, data at a pedestrian height of 1.5 m were selected for averaging and analysis. The accuracy of ENVI-met in simulating pollutant dispersion has been validated by numerous studies [21–23]. At the same time, in order to eliminate boundary interference and ensure the authenticity of the physical environment in the core area, data from a residential building and the inter residential area in the middle of the model were extracted for analysis (Figure 2a).

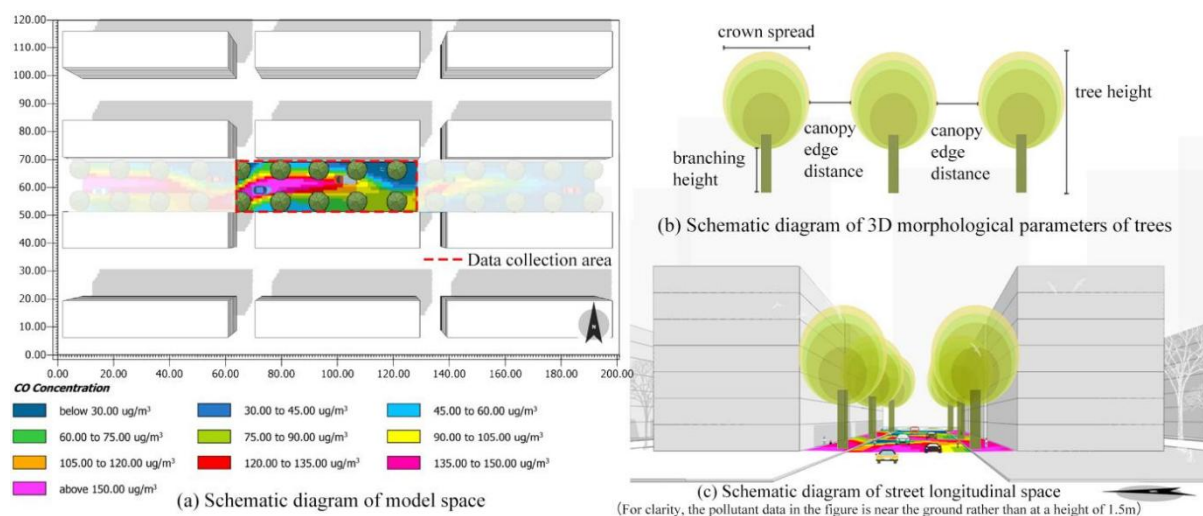


Figure 2. Schematic diagram of numerical model and data collection.

Table 2. ENVI-met Simulation Parameter Settings.

Simulation area size (grid)	Site length (x) × width (y) × height (z) = 200 m × 120 m × 48 m (grids: 200 (x) × 120 (y) × 32 (z), vertical-grid (z) starts to increase after 23m, increasing factor 20%) Building length × width × height = 54 m × 12 m × 21 m
Spatial resolution	1 m × 1 m × 1 m
Simulation running period	From 17:00 on 2 August 2024 to 23:00 on 3 August 2024
Meteorological file	Hourly meteorological data of Jinghe National Meteorological Station on that day
Greening conditions	Greening conditions with 4 different tree heights + 4 different branch point heights + 4 different crown amplitudes + 4 different crown edge distances
Leaf area density	0.4 m ² /m ³
Wind speed and direction	Speed: 2.4 m/s at 10 m height; Direction: North-east
Boundary condition	Advanced detailed meteorology

Table 3. Hourly meteorological data on August 3rd.

Time	Air Temperature (°C)	Relative Humidity (%)	Time	Air Temperature (°C)	Relative Humidity (%)
00:00	30.5	79.2	12:00	33.2	63.2
01:00	29.8	81.3	13:00	32.5	63.3
02:00	29.5	82.5	14:00	32.1	74.4
03:00	28.8	84.3	15:00	33.2	61.3
04:00	28.6	83.3	16:00	33.4	58.2
05:00	28.1	84.1	17:00	32	62.2
06:00	28.2	83.3	18:00	32	62.2
07:00	28.4	81.2	19:00	31.1	63.1
08:00	28.7	70.1	20:00	30.6	68.5
09:00	29.7	77.2	21:00	29	76.6
10:00	30.6	73.4	22:00	28.2	76.5
11:00	32.4	66.2	23:00	27.4	79.2

2.3. Identification of Key Factors

After obtaining the simulation results, range analysis was first conducted to intuitively assess the relative importance of each factor. The core logic of range analysis involves calculating the average CO concentration (i.e., K1, K2, K3, K4) corresponding to each level of a given factor, then subtracting the minimum value from the maximum value to obtain the range (R value). A larger R value indicates that variations in the factor's levels cause more significant fluctuations in CO concentration, thereby assigning a higher weight to that factor. Additionally, to address the statistical masking issue of “no significant effects” often caused by insufficient degrees of freedom in small-sample orthogonal experiments, the study introduced rigorous error pooling techniques. By reducing the dimensionality of minor factors with weak contributions (identified in the results as tree height) and incorporating them into the residual term, the core signals were amplified. Based on the pooled analysis of variance and contribution analysis, the dominant factors controlling CO concentration were precisely identified.

2.4. Mathematical Model Development

After identifying the dominant factors, the study employed multiple stepwise regression analyses to construct a predictive model. The algorithm automatically eliminated statistically insignificant redundant variables, thereby avoiding the risks of multicollinearity and over-fitting. Ultimately, a multivariate linear equation with high statistical significance was fitted, achieving a transition from qualitative trends to quantitative weighting and revealing the specific positive and negative physical synergistic effects of various factors in pollutant dispersion.

2.5. Generalization Capability Testing

To overcome the limitations of the original orthogonal sample points and ensure the engineering practicality of the predictive equations, the study adopted the principle of restricted random sampling. Under objective physical boundary constraints, a computer random seed was used to conduct an equal-probability blind selection from the unsimulated combinations, resulting in the four experimental groups listed in Table 4 as a test set independent of the orthogonal experimental training set. By comparing the mean absolute percentage error and root mean square error between the model predictions for the test set experimental groups and the new simulated actual values, the generalization ability and robustness of the regression model were rigorously tested, ensuring that these research findings can be effectively applied to the quantitative guidance and optimized design of urban neighborhood greening patterns.

Table 4. Specific Combinations of the Test Set.

Test ID	Factor A: Tree Height (m)	Factor B: Branching Height (m)	Factor C: Crown Spread (m)	Factor D: Canopy Edge Distance (m)
1	19	4	6	2
2	15	5	7	0
3	19	4	9	0
4	14	4	7	1

3. Results

3.1. Analysis of the Effect of Tree Three-Dimensional Parameters on CO Concentration

3.1.1. Analysis of CO Concentrations on Streets

Figures 3 and 4 show that the overall patterns of CO concentration distribution are similar across all experimental groups: CO concentrations are lower in the northeast and northwest corners. This may be due to the model's boundary wind direction being set to the prevailing northeast wind in Xi'an, with winds blowing from the upwind direction through gaps between buildings, carrying away CO from the northeast and northwest corners; CO concentrations are also lower along the southern edge near the building area. This is because the northeast-bound incoming wind encounters obstruction from the southern buildings, causing part of the airflow to divert upward or toward the northwest, thereby carrying away the CO in that area; CO concentrations are higher in the western part of the road's central section, with all points exceeding $100 \mu\text{g}/\text{m}^3$ concentrated there. This may be due to the wind blowing from both the north and south sides of the road, causing CO to accumulate in this area.

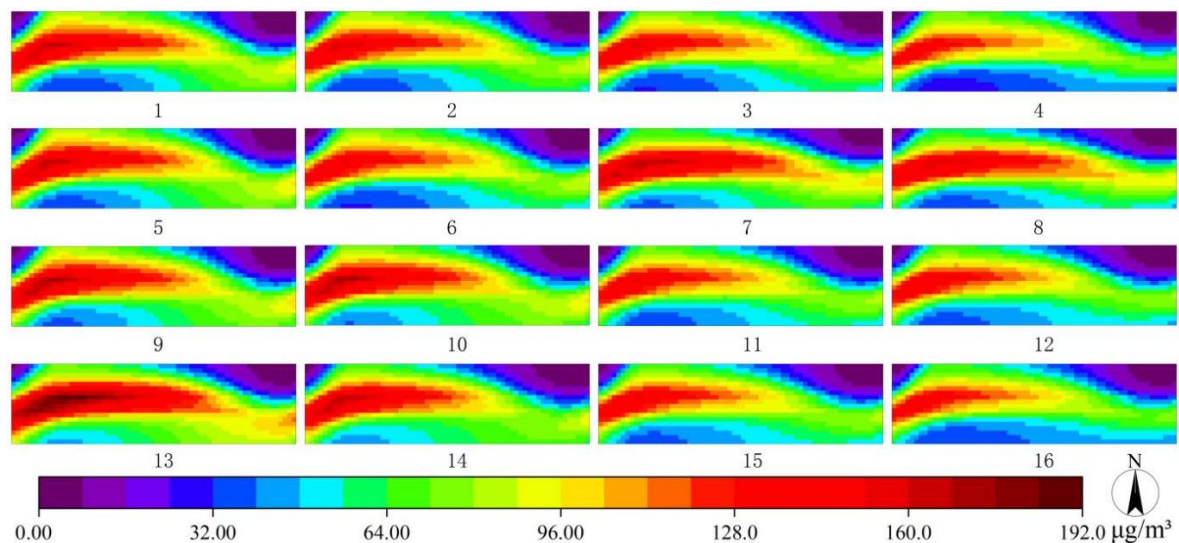


Figure 3. Plan view of CO concentration distribution at pedestrian height along the experimental streets for each group (Groups 1–16 correspond to the orthogonal experimental combinations listed in Table 1).

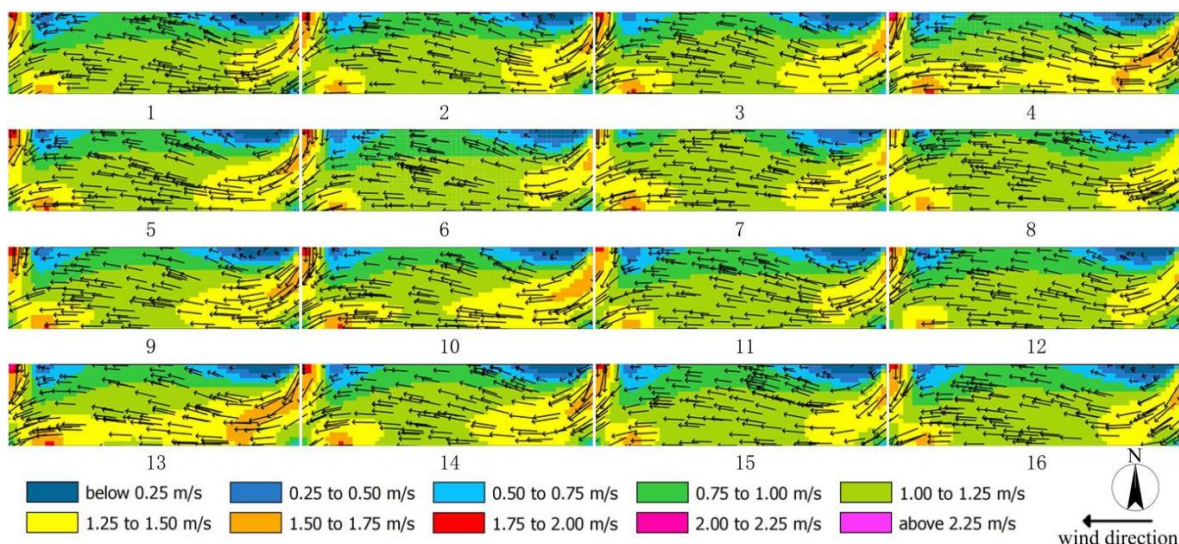


Figure 4. Distribution of Wind Speed and Direction at Pedestrian Height on Experimental Streets in Each Group (Groups 1–16 correspond to the orthogonal experimental combinations listed in Table 1).

Furthermore, as shown in Figures 3 and 5, the minimum CO concentrations across the experimental groups fluctuated minimally, while the maximum values fluctuated significantly. Experiment 13 recorded a maximum value exceeding $188 \mu\text{g}/\text{m}^3$, while Experiments 9 and 10 exceeded $170 \mu\text{g}/\text{m}^3$. In contrast, Experiments 4 and 16 exhibited lower CO concentrations, both below $145 \mu\text{g}/\text{m}^3$. Regarding the box length (25–75%), there was little

variation. Experiment 13 had the longest box length, with a difference of $55.82 \mu\text{g}/\text{m}^3$ between the third and first quartiles, while Experiment 12 had the shortest, with a difference of $42.62 \mu\text{g}/\text{m}^3$ between the third and first quartiles. The median values in each experimental group were close to the mean, indicating a symmetrical data distribution typical of data without strong skewness. The mean values exhibited a concentrated distribution with localized variations; the maximum mean was $88.15 \mu\text{g}/\text{m}^3$, and the minimum was $63.5 \mu\text{g}/\text{m}^3$. The overall average CO concentration across all experimental groups was approximately $75.52 \mu\text{g}/\text{m}^3$. The average CO concentration in most experiments (11 groups) fell below $75.52 \mu\text{g}/\text{m}^3$, accounting for 68.75% of the total, indicating that CO concentrations remained in a relatively low range under most parameter combinations. However, the difference between the highest and lowest average values was significant, reaching $24.65 \mu\text{g}/\text{m}^3$, suggesting that different parameter combinations had markedly different effects on regulating the overall CO concentration along the street.

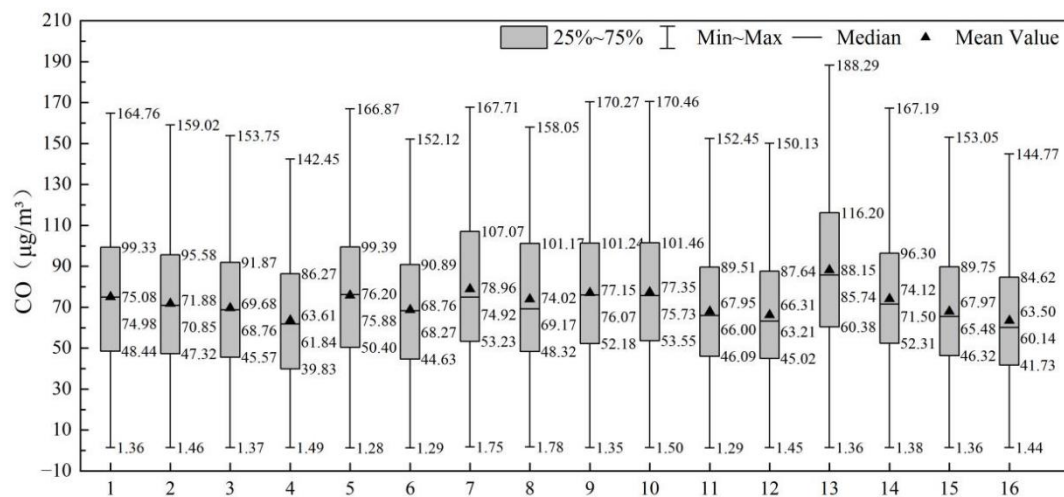


Figure 5. Box plots of CO concentrations at pedestrian height on experimental streets (Groups 1–16 correspond to the orthogonal experimental combinations listed in Table 1).

3.1.2. Analysis of the Strength of the Effect of Tree Three-Dimensional Parameters on CO Concentration

The summary of the range analysis results is shown in Table 5. The data indicate that the ranges of the four tree morphological parameters exhibit a very distinct hierarchical pattern. The strict ranking of range values is: branching height ($R = 12.21$) > crown spread ($R = 8.20$) > canopy edge distance ($R = 6.13$) > tree height ($R = 4.34$). This ranking quantitatively confirms that branching height and crown spread are the two dominant factors controlling CO concentrations in the street canyon. After clarifying the primary and secondary factors, a closer examination of the trends in the K-values of the core factors provides intuitive evidence for the physical mechanisms of the microclimate. First, regarding branching height, which ranked first, the mean CO concentrations at the four corresponding levels were 79.07, 73.03, 71.14, and 66.86, respectively, presenting a highly regular monotonically decreasing curve. Physically, this implies that as branch points rise, the lower street space—previously blocked by dense foliage—is released, opening up ventilation corridors at pedestrian height and allowing vehicle exhaust to be efficiently carried away by lateral airflow.

Table 5. Range Analysis.

Range Ranking	Experimental Factor	Level 1 (K1)	Level 2 (K2)	Level 3 (K3)	Level 4 (K4)	Range (R)	Physical Trend Observations
1	Branching height (B)	79.07 (4 m)	73.03 (5 m)	71.14 (6 m)	66.86 (7 m)	12.21	CO concentrations decrease significantly with increasing branching height
2	Crown spread (C)	68.82 (6 m)	70.51 (7 m)	73.74 (8 m)	77.02 (9 m)	8.2	As the amplitude increases, the CO concentration rises significantly
3	Canopy edge distance (D)	73.62 (0 m)	75.50 (1 m)	71.60 (2 m)	69.37 (3 m)	6.13	There is some volatility, but the overall trend is downward
4	Tree height (A)	70.06 (14 m)	74.41 (16 m)	72.19 (18 m)	73.44 (20 m)	4.34	Minimal fluctuations; no obvious linear pattern

3.1.3. Main Effects of Tree Morphological Factors on CO Concentration

As illustrated in Figure 6, the main effect trends derived from the range analysis clearly demonstrate the directional impact of each morphological factor on the CO concentration. Specifically, the mean CO concentration

exhibits a consistent, monotonic decrease as the branching height increases from level 1 to level 4 (Figure 6b). This graphical trend reinforces the dominant role of vertical clearance beneath the canopy in promoting aerodynamic flushing, as corroborated by the regression and ANOVA results in Table 6. Conversely, crown spread (Figure 6c) displays a highly regular, monotonic upward trajectory, with the mean CO concentration rising steadily across the four levels. This distinct positive correlation reveals that excessive lateral expansion of tree crowns significantly intensifies aerodynamic drag, creating a heavy canopy blocking effect that hampers airflow circulation and leads to the severe entrapment of pedestrian-level vehicle exhaust. For canopy edge distance (Figure 6d), the curve presents an overall descending trend despite a minor localized fluctuation at level 2. This negative trend demonstrates that widening the spacing between adjacent crowns effectively enhances the street's longitudinal spatial permeability, allowing wind fields to pass through more freely to dilute bottom-level pollution. In sharp contrast, the trend line for tree height (Figure 6a) remains relatively flat, showing only minor fluctuations without a clear monotonic or linear pattern. This stagnant trajectory visually confirms that variations in tree body height exert a negligible direct impact on near-surface pollutant dispersion within the studied canyon configuration, aligning with its low range value ranking. In summary, univariate analysis confirms that branching height and crown spread are the key factors driving variations in CO concentration. These results corroborate the conclusions of the range analysis, providing clear quantitative evidence for regulating air quality through tree morphological design.

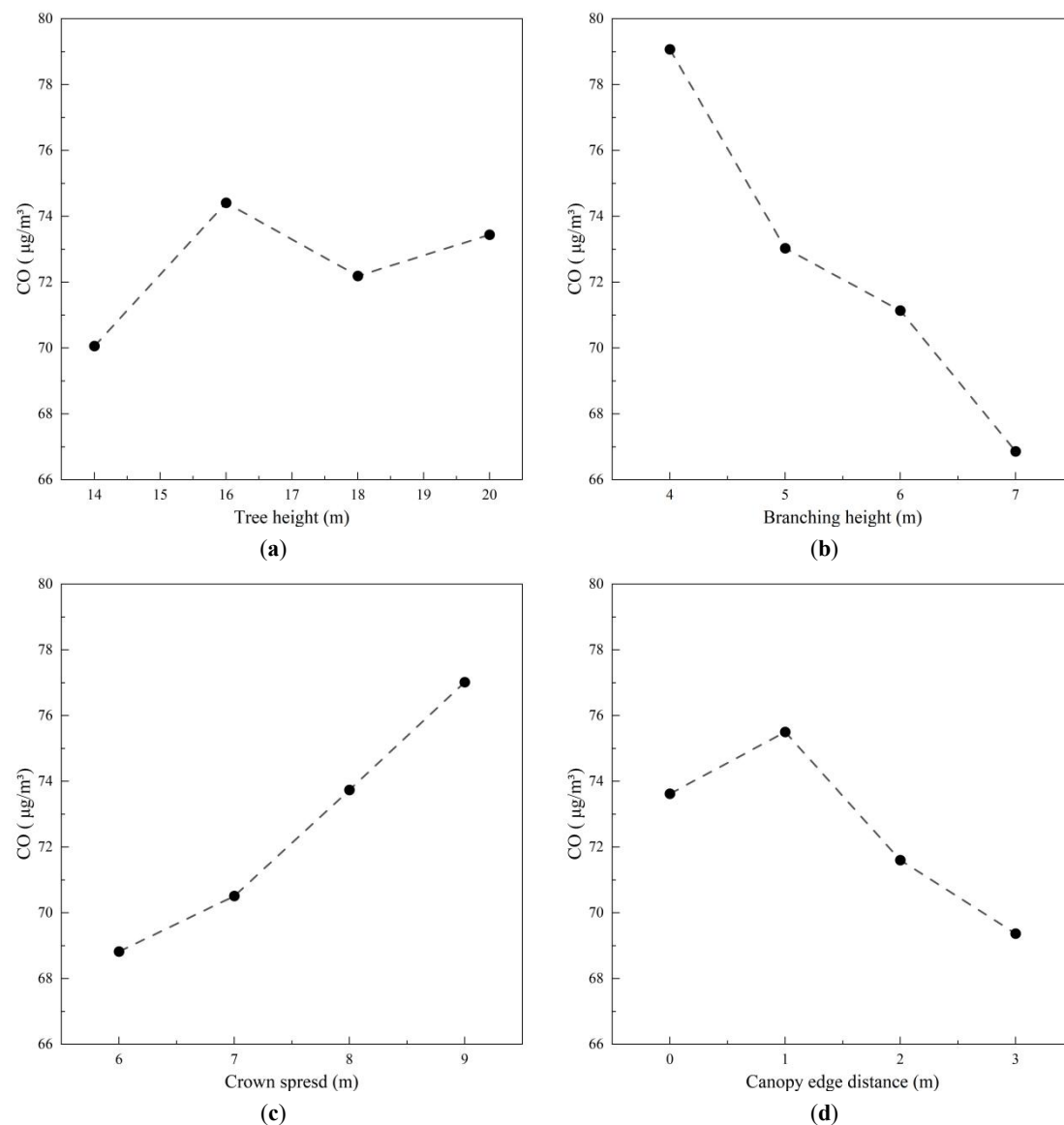


Figure 6. Main effects of tree morphological factors on pedestrian-level CO concentration (points represent the mean values at each orthogonal level. **(a)** Trend between tree height and CO concentration. **(b)** Trend between branching height and CO concentration. **(c)** Trend between crown spread and CO concentration. **(d)** Trend between canopy edge distance and CO concentration.

Table 6. Analysis of variance and contribution rates for CO concentration (after error-pooling).

Source of Variance	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Square (MS)	F-Value	p-Value	Contribution Rate (%)	Significance Test
Branching height (B)	308.14	3	102.71	9.13	0.012	49.97%	Significant
Crown spread (C)	157.73	3	52.58	4.67	0.052	25.58%	Marginally significant
Canopy edge distance (D)	83.33	3	27.78	2.47	0.159	13.51%	Not significant
Pooling error	67.49	6	11.25	-	-	10.95%	-
Total	616.7	15	-	-	-	100.00%	-

3.1.4. Analysis of Interactions Among Tree Three-Dimensional Parameters

The regulatory effects of trees' three-dimensional parameters on CO concentrations in the street exhibit multidimensional interactions; these effects are not a linear superposition of individual dimensional indicators but rather arise through the combined influence of branching height, crown spread, and tree height (A, B, and C). The following sections provide a detailed analysis of each interaction.

As shown in Figure 7a, the combination of branching height (B) and tree height (A) has a significant effect on CO concentration. When the branching height is 4 m, CO concentration generally increases with tree height, reaching a peak at 20 m ($88.15 \mu\text{g}/\text{m}^3$), indicating that a combination of low branch points and tall trees tends to lead to pollutant accumulation. When the branching height was 7 m, the CO concentration first increased and then decreased with increasing tree height, dropping to a relatively low level ($63.50 \mu\text{g}/\text{m}^3$) at 20 m, indicating that a high branching combined with a tall tree body promotes vertical ventilation. When the branching height was 5 m and 6 m, CO concentrations fluctuated with height without a clear monotonic pattern, reflecting that the influence of tree height at medium branching heights is modulated by other factors.

Figure 7b reveals the interaction between crown spread (C) and tree height (A). When the crown spread was 6 m (narrow crown), CO concentration decreased continuously with increasing tree height (from $75.08 \mu\text{g}/\text{m}^3$ at 14 m to $63.50 \mu\text{g}/\text{m}^3$ at 20 m); the combination of a narrow crown and a tall tree formed a better vertical channel, which was conducive to pollutant dispersion. Conversely, when the crown spread is 9 m (wide crown), CO concentrations rise significantly with increasing tree height (from $63.61 \mu\text{g}/\text{m}^3$ at 14 m to $88.15 \mu\text{g}/\text{m}^3$ at 20 m); the combination of a wide crown and a tall tree trunk tends to create a shading effect, hindering near-surface air circulation. Under moderate crown spreads (7 m, 8 m), CO concentrations exhibited a pattern of first increasing and then decreasing, or fluctuating, with height, indicating the presence of a critical crown-to-height ratio (crown spread/tree height) that influences ventilation efficiency.

The interaction between the canopy edge distance (D) and tree height (A) exhibits complex nonlinear characteristics (Figure 7c). Specifically, when the canopy edge distance is small (0 m and 1 m), CO concentrations fluctuate with changes in tree height, showing no obvious monotonic trend, indicating that under densely arranged canopies, the influence of tree height on pollutant distribution is strongly modulated by other factors. However, when the canopy edge distance increased to 2 m and 3 m, CO concentrations followed a trend of first increasing and then decreasing with tree height: the concentration peak occurred at 18 m for both distances, but the location of the peak differed—at a canopy edge distance of 2 m, the concentration corresponding to a 20-m-tall tree was lower; at a 3 m canopy edge distance, the concentration corresponding to a 14 m tall tree was lower. This reflects a threshold effect in the interaction between canopy edge distance and tree height: a moderate canopy edge distance combined with tall trees promotes diffusion (e.g., 2 m + 20 m), while an excessively large canopy edge distance may disrupt the continuity of canopy cover and requires coordination with shorter trees to achieve better results (e.g., 3 m + 14 m). Overall, the interaction between canopy edge distance (D) and tree height (A) cannot be summarized by a simple linear relationship; in practical design, comprehensive judgment must be made by considering parameters such as branching height and canopy spread.

The synergistic effect of branching height and crown spread is the core mechanism regulating street ventilation (Figure 7d). When the branching height is 4 m, and the crown spread is 9 m, CO concentration reaches its peak ($88.15 \mu\text{g}/\text{m}^3$); this “low branching height–wide crown” combination exacerbates pollutant retention. Conversely, when the branching height is 7 m, and the crown spread is 6 m, CO concentrations drop to the lowest level ($63.50 \mu\text{g}/\text{m}^3$), indicating that the “high branching point–narrow crown” combination significantly improves dispersion conditions. This trend aligns with the direction of the main effects: both high branching points and narrow crowns favor lower concentrations, and their combined effect is the strongest.

The interaction between branching height and distance to the canopy edge was also significant (Figure 7e). The highest CO concentration ($88.15 \mu\text{g}/\text{m}^3$) was observed when the branching height was 4 m, and the canopy

edge distance was 1 m; the lowest concentration ($63.50 \mu\text{g}/\text{m}^3$) was observed when the branching height was 7 m, and the canopy edge distance was 2 m. Notably, when the canopy edge distance was 2 m, concentration differences varied significantly across different branching heights, indicating that this distance favors high branch points and disadvantages low branch points; whereas when the canopy edge distance was 1 m, concentrations were extremely high at low branch points and moderate at high branch points, suggesting that 1 m may be a sensitivity threshold for low branch points.

The interaction between crown spread and canopy edge distance further confirms the importance of morphological matching (Figure 7f). The combination of a narrow canopy (6 m) and a 2 m canopy edge distance resulted in a lower CO concentration ($63.50 \mu\text{g}/\text{m}^3$), whereas the combination of a wide canopy (9 m) and a 1 m canopy edge distance yielded the highest concentration ($88.15 \mu\text{g}/\text{m}^3$). A wide canopy requires a larger canopy edge distance (e.g., 3 m) to achieve a lower concentration ($63.61 \mu\text{g}/\text{m}^3$), whereas a narrow canopy performs best at a moderate canopy edge distance (2 m). This indicates that crown spread and canopy edge distance must be coordinated to balance shading and ventilation.

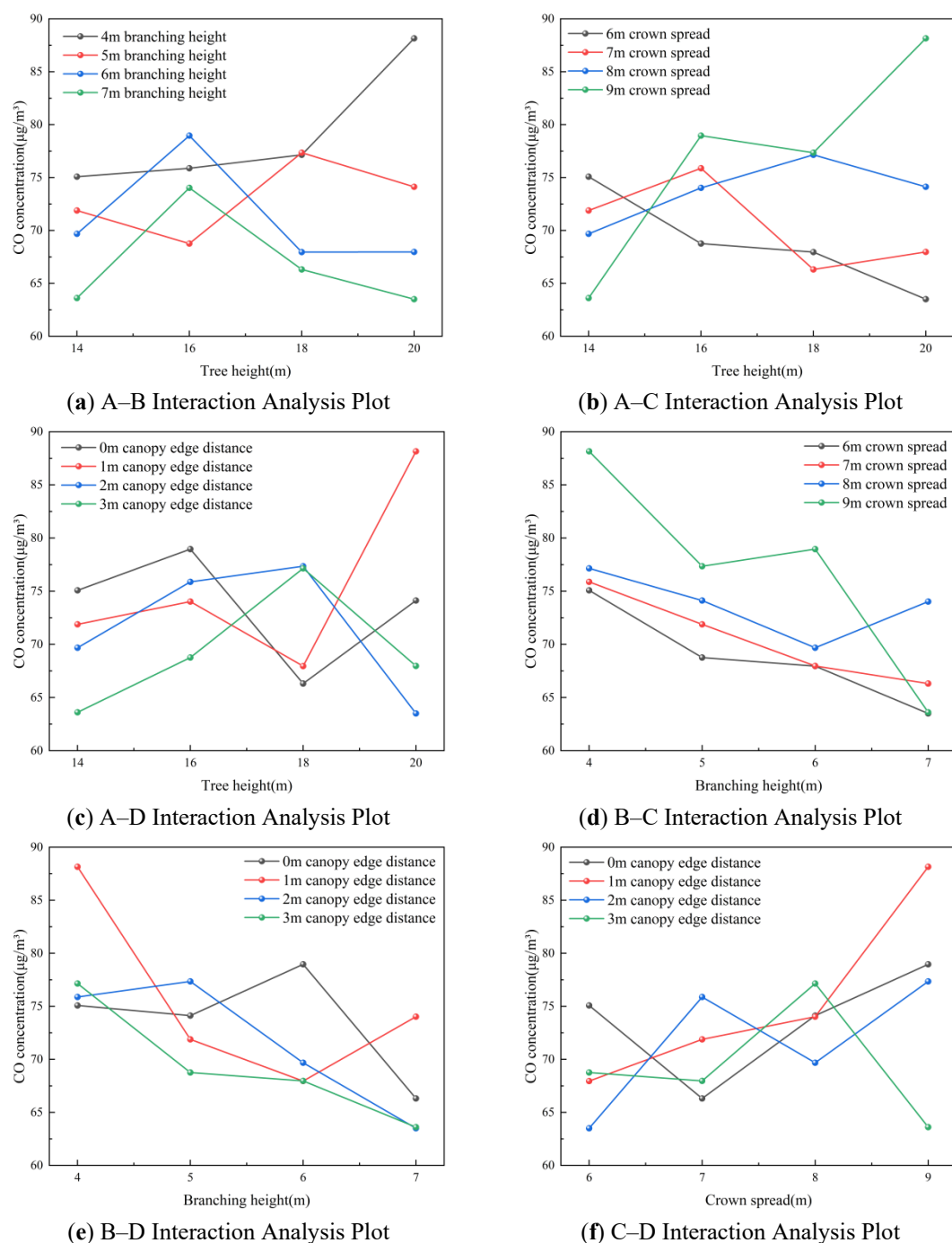


Figure 7. Interaction Analysis Plot of Tree Three-Dimensional Parameters.

In summary, the three-dimensional parameters of trees collectively influence the distribution of CO concentrations in the street through multidimensional interactions. Optimal configurations were observed in two combinations: first, a combination of high branching height (7 m), narrow canopy spread (6 m), moderate canopy edge distance (2 m), and tall trees (20 m) results in $63.50 \mu\text{g}/\text{m}^3$ CO concentration; and second, a combination of high branching height (7 m), wide canopy (9 m), large canopy edge distance (3 m), and short trees (14 m) (CO concentration: $63.61 \mu\text{g}/\text{m}^3$). The worst configuration was a combination of a low branching height (4 m), wide canopy (9 m), 1 m canopy edge distance, and tall trees (20 m) ($88.15 \mu\text{g}/\text{m}^3$). The results indicate that optimizing the relationship between branching height, crown spread, and canopy edge distance can significantly improve street ventilation efficiency, providing quantitative evidence for street greening design.

3.2. Analysis of the Combined Effects of Tree Three-Dimensional Parameters on CO Concentration

3.2.1. Analysis of Variance and Contribution Rates

Table 6 presents the results of the analysis of variance (ANOVA) and contribution rates following error pooling, aiming to precisely quantify the actual explanatory power of each tree morphological parameter on fluctuations in micro-environmental CO concentrations. To enhance the power of statistical testing, the study combined “tree height”, which had the smallest range and minimal influence, with the initial residuals to construct a “pooled error” with 6 degrees of freedom, thereby eliminating the interference of systematic noise. The analysis revealed that branching height is the primary factor driving CO concentration variations, with an independent contribution rate as high as 49.97% and statistical significance ($p = 0.012 < 0.05$). Crown spread serves as the secondary dominant factor, contributing 25.58% and exhibiting marginal significance ($p = 0.052 \approx 0.05$). Together, these two factors account for over 75% of the variation in concentration, providing quantitative confirmation that the “opening of the lower ventilation corridor” and the “aerodynamic shielding of the upper canopy” are the most critical physical mechanisms controlling the dissipation of pollution in street canyons. Furthermore, although the canopy edge distance did not reach the significance threshold in the ANOVA due to local nonlinear fluctuations ($p = 0.159$), its substantial contribution rate of 13.51% indicates that it still exerts a significant physical influence; therefore, it was retained to prevent model distortion. Ultimately, the pooled error accounting for unknown environmental disturbances accounted for only 10.95%. This extremely low error proportion demonstrates that the orthogonal experimental design successfully captured the primary factors influencing CO diffusion, and the extracted patterns possess extremely high statistical robustness and practical significance.

3.2.2. Multiple Linear Regression Analysis

Based on a least-squares fit and following a multivariate stepwise regression analysis, the mathematical relationship between CO concentration and the various morphological factors (B, C, D) was established as follows:

$$Y_{\text{CO}} = 75.33 - 3.85 * B + 2.78 * C - 1.66 * D \quad (1)$$

where:

Y_{CO} —CO concentration ($\mu\text{g}/\text{m}^3$);

B—Branching height (m);

C—Crown spread (m);

D—Canopy edge distance (m).

The multiple regression model for the relationship between tree 3D parameters and CO concentration is shown in Equation (1), and the comprehensive analysis results are presented in Table 7. As shown in the table, the adjusted R^2 of the regression model is 0.77, indicating that the model explains 77% of the variation in CO concentration, suggesting a high level of model fit. The Durbin-Watson statistic is 2.103, which is extremely close to the ideal value of 2. This indicates that the residuals from each sample are independent of one another, with no autocorrelation, suggesting that the model is well-specified. The model’s F-statistic is 18.400, with $p < 0.001$, proving that this multiple regression equation is highly statistically significant overall. The p -values for both branching height and crown spread are less than 0.01, indicating that their respective effects are highly significant. However, it is worth noting that when conducting a one-way ANOVA on crown spread (C) alone (without controlling for other variables), the p -value was 0.052, indicating only marginal significance. In the multiple regression model, the simultaneous inclusion of covariates such as branch point height and edge distance effectively reduced residual variance and controlled for confounding factors, thereby highlighting the net effect of crown spread—its p -value was less than 0.05, reaching the level of significance. From the standardized regression coefficients, comparing the absolute magnitude of influence among the factors, branching height ($|-0.693|$) >

crown spread ($|0.501| > \text{canopy edge distance } |-0.300|$), which proves that branching height has the greatest contribution to pollutant dispersion. The p -values for all three independent variables were less than 0.05 (with B being highly significant, C highly significant, and D significant), indicating that their respective effects on CO concentration are valid and reliable. A VIF of 1.000 indicates that the VIF values for all variables are 1.0, suggesting that there is absolutely no risk of multicollinearity or mutual interference among the independent variables, and that the model coefficients are clean and robust.

Table 7. Comprehensive Analysis of the Multiple Regression Model for CO Concentration Based on Tree Three-Dimensional Parameters.

Adjusted R ²	Durbin-Watson	F	p-Value	Independent Variables	Standardized Regression Coefficient	t	p-Value	VIF
0.77	2.103	18.400	<0.001	Branching height (m)	−0.693	−5.684	<0.001 (significant)	1.0
				Crown spread (m)	0.501	4.107	0.001 (significant)	1.0
				Canopy edge distance (m)	−0.300	−2.455	0.030 (significant)	1.0
				Constant term	-	11.723	<0.001	-

3.2.3. Generalization Test Analysis

Table 8 shows that the results of the generalization test indicate that when the multiple regression model is applied to unknown parameter combinations, the MAPE between the predicted values and the actual values simulated by ENVI-met is only 2.15%, the RMSE is as low as 1.90, and the R² from the external independent validation reaches 0.76. This fully confirms that the constructed CO concentration prediction model for the neighborhood micro-environment not only avoids the limitations of orthogonal sample points and the risk of over-fitting but also possesses extremely high generalization capability and practical engineering prediction value.

Table 8. Generalization Test Results.

Test ID	Predicted CO Concentration from Regression Model (μg/m ³)	ENVI-Met Simulated CO Concentration (μg/m ³)	MAPE	RMSE	R ²
1	73.29	73.25	2.15%	1.90 μg/m ³	0.76
2	75.54	73.27			
3	84.95	82.78			
4	77.73	75.60			

4. Discussion

4.1. Mechanisms of Individual Morphological Parameters Affecting Pollutant Dispersion

Through orthogonal experiments and numerical simulations, this study found that branching height is the primary controlling factor influencing CO concentrations at pedestrian height in street canyons (contribution rate: 49.97%) and exhibits a highly significant negative correlation with CO concentrations. This result is consistent with the conclusions of the CFD simulations by Guo et al.—increasing the height of the canopy can effectively open up the space beneath the canopy, promoting horizontal and vertical airflow exchange [24]. He et al. similarly confirmed through ENVI-met studies in hot-humid urban blocks that street trees with high branching height significantly reduce traffic-related PM_{2.5} concentrations, with this effect being more pronounced in narrow street canyons [21]. The underlying mechanism is that branching height determines the vertical clearance of the trunk space: a high branch point creates a well-ventilated “air corridor” beneath the canopy, which enhances momentum exchange between the near-surface layer and upper airflow while reducing direct obstruction of horizontal inflow, thereby accelerating lateral transport and vertical dilution of vehicle emissions. Thus, the dominant role of branching height appears robust across different climates and canyon geometries.

In contrast to branching height, crown spread shows a significant positive correlation with CO concentrations, meaning that wider crowns actually exacerbate pollutant accumulation. This result challenges the conventional intuition that “larger canopies lead to stronger adsorption” and supports a mechanism dominated by aerodynamic blockage. Maison et al. found through CFD parameterization that canopies can reduce average horizontal wind speed by up to 68% and vertical exchange coefficients by 23%, with these effects increasing as leaf area index and

canopy volume increase [25]. Li et al. also noted that while increasing leaf area density or planting density improves thermal comfort, it leads to greater pollutant retention; tall trees with low near-surface leaf area perform best under high wind speed conditions [26]. The core mechanism here is that a wide crown substantially increases aerodynamic roughness and drag, causing a sharp decrease in wind speed and enhanced turbulent dissipation, which weakens convective diffusion; meanwhile, the deposition capacity of foliage is limited and cannot offset the blocking effect. Therefore, wide canopies primarily degrade near-surface air quality through increased aerodynamic resistance rather than adsorption.

Furthermore, edge distance showed a significant negative correlation in this study, consistent with the conclusion by Gromke and Ruck that increasing tree spacing can reduce pollutant concentrations [27]. The mechanism is that a larger edge distance provides buffer space between the crown and the source, allowing some lateral dilution before the plume reaches the canopy. Tree height showed a weak positive correlation, possibly because taller crowns increase total canopy volume and overall drag, offsetting any vertical uplift benefit; its net effect depends on interactions with other parameters.

4.2. Synergistic Effects among Multiple Parameters and the Causes of Optimal/Worst Configurations

This study also identified the optimal and worst-case combinations of morphological traits: the lowest CO concentrations occurred in trees with “high branch points + narrow crowns + moderate edge distance + tall stature”, while the highest concentrations corresponded to “low branch points + wide crowns + 1 m edge distance + tall stature”. This suggests that the spatial alignment between branching height and crown spread is key to determining ventilation efficiency, rather than the independent action of individual factors. When branching height is high and crown spread is narrow, a large open space is created under the canopy, allowing horizontal airflow to pass through the trunk zone and carry away pollutants; the narrow crown reduces overall blockage, and the two factors synergistically enhance air exchange. In contrast, low branch point combined with wide crown forms a dense “canopy barrier” that nearly blocks near-surface flow, trapping emissions at breathing height. Tang et al. found that higher crown extent and trunk height prolong the residence time of pollutants [28]. Wang et al. emphasize in their review that the obstructing effect of tree canopy cover is closely related to the street canyon aspect ratio, wind direction, and source intensity, and that there is no universally optimal tree form [29]. Guo et al. similarly argue that tree-based air quality improvement requires targeted design that integrates tree form, street canyon geometry, and meteorological conditions [24]. Our interaction analysis further revealed that when crown spread is large (e.g., 9 m), planners must simultaneously increase edge distance (e.g., 3 m) to avoid severe accumulation; conversely, dense planting (1 m edge distance) with low branching height should be strictly avoided, as it creates a “micro-canal” effect trapping pollutants at pedestrian level. Therefore, street tree configuration should shift from “single-parameter optimization” to “multi-parameter collaborative design”, physically balancing shading against ventilation, which depends on under-crown void fraction and overall drag coefficient.

4.3. Limitations and Planning Implications

Although the adjusted R^2 of the multiple regression model in this study was 0.77 and the MAPE was only 2.15%, indicating that the model has good generalization ability, several limitations remain. First, CO, as a tracer, failed to distinguish the dynamic variations in emissions from traffic sources; future studies could incorporate simultaneous observations of multiple pollutants. Second, seasonal and phenological differences were not considered, whereas Maison et al. noted through LAI parameterization that ventilation conditions differ significantly between the leafless (dormant) period and the full-leaf period, and He et al. also suggested that street tree morphological parameters should account for seasonal requirements [21,25]. Finally, this study examined only single-row street tree configurations and did not address complex scenarios such as multi-row green belts or vertical green walls, which may introduce different turbulent exchange mechanisms. Nevertheless, through orthogonal experiments and cross-validation of multiple methods, this study provides quantifiable evidence for the scientific configuration of street trees in urban blocks: in street environments where ensuring ventilation beneath the canopy is a priority, increasing branching height and moderately controlling canopy spread should be the primary design principles, while an overreliance on tree height requires reevaluation.

The findings of this study provide a quantitative foundation for the topological optimization of urban street greenery, moving beyond simple two-dimensional green coverage metrics. From a spatial planning perspective, the topological structure of street trees dictates the aerodynamic permeability of the near-surface layer. For high-density urban street canyons, such as those in the old city of Xi'an, planners should prioritize tree species with natural morphological traits characterized by a high branch point height and a narrow crown. This specific topological combination effectively expands the clearance beneath the canopy, facilitating the lateral dissipation

of vehicle emissions. Furthermore, these quantitative results offer actionable strategies for resolving the trade-off between thermal comfort (shading) and pollutant dispersion. If landscape requirements necessitate the use of trees with wide crowns (e.g., 9 m), our interaction analysis reveals that planners must simultaneously increase the canopy edge distance to a wider spacing (e.g., 3 m) to prevent severe pollutant accumulation. Conversely, dense planting schemes (e.g., 1 m canopy edge distance) with low branch point heights must be strictly avoided, as they form a micro-canal that traps pollutants at the pedestrian level. Therefore, these quantitative design guidelines allow for precise, site-specific topological optimization during the selection, planting, and pruning phases of urban green space management.

5. Conclusions

This study combined ENVI-met numerical simulation with orthogonal experimental design to systematically quantify the regulatory effects of four three-dimensional parameters—tree height (A), branching height (B), crown spread (C), and canopy edge distance (D)—on CO concentrations under the canopy in urban streets. It clarified the influence patterns, interaction effects, and optimization directions of each parameter. The main conclusions are as follows:

1. The order of influence and optimal combination of factors were identified. The intensity of influence on CO concentration, from primary to secondary, is as follows: branching height (B) > crown spread (C) > canopy edge distance (D) > tree height (A). The simulated lowest CO concentration ($63.50 \mu\text{g}/\text{m}^3$) occurred in the combination of “tree height 20 m, branching height 7 m, crown spread 6 m, and canopy edge distance 2 m”, demonstrating the synergistic advantages of a high branching, narrow crown, and moderate canopy edge distance; The second-lowest concentration ($63.61 \mu\text{g}/\text{m}^3$) occurred in the combination of “14 m, 7 m, 9 m, 3 m”, demonstrating another effective combination of a high branching point, wide crown, and large canopy edge distance.
2. The analysis revealed the key influence of interactions among morphological factors. The effects of tree morphological factors are not independent; complex interactions exist among them. The interaction between branching height and crown spread is most significant: a combination of high branching height and a narrow crown promotes dispersion, whereas a combination of low branching height and a wide crown leads to severe pollutant accumulation (maximum concentration of $88.15 \mu\text{g}/\text{m}^3$, corresponding to 20 m, 4 m, 9 m, 1 m). Design should avoid optimizing a single indicator in isolation; instead, it should focus on the overall synergy among branching height, crown spread, and canopy edge distance.
3. The study distinguished between statistical influence and engineering contribution, identified core regulatory factors, and, through contribution analysis, demonstrated that branching height (49.97%) and crown spread (25.58%) are the dominant factors driving changes in CO concentration, with a combined contribution rate exceeding 75%, indicating clear engineering regulatory value. Canopy edge distance (D) is a statistically significant predictor ($p = 0.03$) and participates in important synergistic interactions (e.g., $C \times D$). When fine-tuning models or optimizing complex canopy structures, it should still receive appropriate attention.
4. A quantitative prediction model was established, and key regulatory pathways were identified. Based on multiple linear regression analysis, a quantitative prediction model linking CO concentration to major influencing factors was developed, and its accuracy was verified through generalization tests. The model indicates that, in the practical optimization of street greening structures, increasing branching height, reducing crown spread, and appropriately increasing the canopy edge distance are the most direct and effective technical approaches to reducing CO concentrations under the canopy.

The findings of this study provide a theoretical basis and quantitative tools for the refined design of trees in old street aimed at regulating the dispersion of air pollutants. In the future, the optimization design system for the ecological functions of urban roadside green spaces can be further refined by incorporating the characteristics of additional tree species, variations in road cross-sections, and complex wind field conditions.

Author Contributions

Z.Z.: conceptualization, methodology, supervision, reviewing and editing; D.W. (Dan Wang): data curation, writing—original draft preparation; D.M.: software, validation, investigation, reviewing and editing; C.M.: visualization, investigation; D.W. (Dongliang Wang): investigation; Y.F.: software; Y.X.: validation; W.Y.: methodology, supervision, reviewing. All authors have read and agreed to the published version of the manuscript.

Funding

This research was funded by Youth Program of the National Natural Science Foundation of China (No. 52208032), Natural Science Basic Research Program of Shaanxi (No. 2024JC-YBQN-0488) and Basic Scientific Research Projects of National Universities (No. D5000230151).

Data Availability Statement

The data presented in this study are available on request from the corresponding author.

Acknowledgments

This paper was prepared with the assistance of Yang Yujun from the School of Human Settlements and Civil Engineering at Xi'an Jiaotong University.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

References

1. OECD. *OECD Environmental Outlook to 2050: The Consequences of Inaction—Key Facts and Figures*; OECD Publishing: Paris, France, 2012.
2. Ministry of Public Security of the People's Republic of China. National Motor Vehicle Fleet Reaches 469 Million Vehicles; Number of Drivers Reaches 559 Million. 2026. Available online: <https://www.mps.gov.cn/n2254314/n6409334/c10383533/content.html> (accessed on 27 January 2026). (In Chinese)
3. Yu, Y.; Liu, X.; Tian, D.; et al. Study on the influence of geometric planning elements of street canyons on solar energy potential. *Ind. Archit.* **2020**, *50*, 137–142. (In Chinese)
4. Pan, H.; Wang, W.; Hu, C. The spatiotemporal distribution characteristics of PM_{2.5} and related air quality evaluation in urban street canyons. *Hous. Sci.* **2023**, *43*, 42–47. (In Chinese)
5. Wang, W.; Cheng, X.; Hu, C.; et al. Spatiotemporal distribution characteristics of PM_{2.5} and air quality assessment in urban street canyons: A case study of Changhuai Street, Hefei. *J. Ecol. Environ. Sci.* **2021**, *30*, 2157–2164. (In Chinese)
6. Luo, H.; Liu, X. Different street intersection forms on pollutant dispersion. *Environ. Sci. Surv.* **2024**, *43*, 20–24+35. <https://doi.org/10.13623/j.cnki.hkdk.2024.05.017>. (In Chinese)
7. Zhao, F.; Huang, Z.; Wen, Y.; et al. Study on Ventilation and Pollutant Diffusion of Different Types of Building Blocks. *Build. Energy Environ.* **2022**, *41*, 47–52. (In Chinese)
8. Qiu, Z.; Wang, Z.; Li, W. Influence of Urban Viaduct on the Diffusion and Distribution of Particulate Matter. *China J. Highw. Transp.* **2022**, *35*, 202–210. (In Chinese)
9. Gong, W.; Cui, P.; Huang, Y.; et al. Influence of asymmetric building layout on pollutant diffusion in street canyon. *J. Subtrop. Resour. Environ.* **2025**, *20*, 122–128. <https://doi.org/10.19687/j.cnki.1673-7105.2025.02.015>. (In Chinese)
10. Cui, A.; Miao, C.; He, H.; et al. Spatiotemporal distribution characteristics of atmospheric pollutants in urban street canyons based on mobile observations. *Chin. J. Ecol.* **2022**, *41*, 2035–2042. (In Chinese)
11. Ahmadi, M.; Mirjalily, S.A.A.; Oloomi, S.A.A. Simulation of pollutant dispersion in urban street canyons using hybrid RANS-LES method with two-phase model. *Comput. Fluids* **2020**, *210*, 104676.
12. Zhou, H.; Han, M.; Zhou, T.; et al. Influence of Urban Street Valley Distribution Pattern on Traffic Pollutant Diffusion. *Environ. Sci. Manag.* **2025**, *50*, 33–38. (In Chinese)
13. Liu, W.; Huang, Z.; Zhan, Q.; et al. Numerical modeling of the effects of motor vehicle lanes layout on the transport and dispersion of exhaust pollutants in urban street canyons. *Chin. J. Appl. Ecol.* **2025**, *36*, 671–681. (In Chinese)
14. Miao, C.; Yu, S.; Hu, Y.; et al. How the morphology of urban street canyons affects suspended particulate matter concentration at the pedestrian level: An in-situ investigation. *Sustain. Cities Soc.* **2020**, *55*, 102042.
15. Hu, Y.; Ma, K. A comprehensive simulation study on the effects of urban street greening on air quality and microclimate. *Acta Ecol. Sin.* **2021**, *41*, 1314–1331. (In Chinese)
16. Ren, F.; Bai, Y.; Qiu, Z.; et al. Research progress on roadside vegetation barriers for reducing particulate matter pollution. *Acta Ecol. Sin.* **2022**, *42*, 5177–5186. <https://doi.org/10.5846/stxb202108042131>. (In Chinese)

17. Xu, P.; Li, X.; Lv, G.; et al. Effects of shrub vegetation on the dispersion of motor vehicle pollutants in street canyons. *J. Northeast. Norm. Univ.* **2022**, *54*, 129–135. (In Chinese)
18. Zhao, F.; Zhao, Z. Analysis of the Impact of Urban Green Space Landscape Layout on the Diffusion of Air Pollutants. *Environ. Sci. Manag.* **2025**, *50*, 163–168. (In Chinese)
19. Karttunen, S.; Kurppa, M.; Auvinen, M.; et al. Large-eddy simulation of the optimal street-tree layout for pedestrian-level aerosol particle concentrations: A case study from a city boulevard. *Atmos. Environ. X* **2020**, *6*, 100073.
20. Li, P.; Wang, S.; Wang, Y.; et al. The “micro-canal effect” of urban roadside green belts and its impact on pollutant concentrations in bicycle lanes. *Acta Ecol. Sin.* **2011**, *31*, 2888–2896. (In Chinese)
21. He, H.; Zhu, Y.; Liu, L.; et al. Effects of roadside trees three-dimensional morphology characteristics on traffic-related PM_{2.5} distribution in hot-humid urban blocks. *Urban Clim.* **2023**, *49*, 101448.
22. Miao, C.; Chen, W.; Yu, S. Assessing Ozone Distribution Vertically and Horizontally in Urban Street Canyons Based on Field Investigation and ENVI-met Modelling. *Buildings* **2022**, *12*, 262.
23. Xiong, N.; Song, H.; Zhou, F.; et al. Simulation of Microclimate and PM_{2.5} Dispersion in Typical Urban Parks in Beijing Based on the ENVI-Met Model. *Sustainability* **2025**, *17*, 7247.
24. Guo, Y.; Xiao, Q.; Ling, C.; et al. The right tree for the right street canyons: An approach of tree species selection for mitigating air pollution. *Build. Environ.* **2023**, *245*, 110886.
25. Maison, A.; Flageul, C.; Carissimo, B.; et al. Parameterizing the aerodynamic effect of trees in street canyons for the street network model MUNICH using the CFD model Code_Saturne. *Atmos. Chem. Phys.* **2022**, *22*, 9369–9388.
26. Li, Z.; Zhang, H.; Juan, Y.-H.; et al. Effects of urban tree planting on thermal comfort and air quality in the street canyon in a subtropical climate. *Sustain. Cities Soc.* **2023**, *91*, 104334.
27. Gromke, C.; Ruck, B. Influence of trees on the dispersion of pollutants in an urban street canyon—Experimental investigation of the flow and concentration field. *Atmos. Environ.* **2007**, *41*, 3287–3302.
28. Tang, Y.-F.; Chen, H.; Yang, M.; et al. Weak geostrophic wind driven ventilation in street canyons with trees and green walls: Cooperating or opposing dispersions of airborne pollutants? *Build. Environ.* **2024**, *259*, 111654.
29. Wang, X.; Zhou, Z.; Xiang, Y.; et al. Effects of street plants on atmospheric particulate dispersion in urban streets: A review. *Environ. Rev.* **2024**, *32*, 114–130.