

Evaluating Street Tree Performance in PM_{2.5} Mitigation under Different Wind Directions: Insights from a CFD Study

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Abstract—This study investigates how street-tree configurations and wind orientation jointly influence PM_{2.5} dispersion in dense urban canyons of tropical cities. Using three-dimensional Computational Fluid Dynamics (CFD) simulations based on the Reynolds-Averaged Navier-Stokes (RANS) model, the research examines nine vegetation scenarios under two prevailing monsoonal wind regimes, perpendicular (west) and parallel (south), along Sukhumvit Road, Samut Prakan Municipality, Thailand. Results reveal that PM_{2.5} mitigation effectiveness is critically dependent on the interaction between configuration and incident wind angle. All tree-scenarios significantly reduced average pedestrian-level (1.5 m) PM_{2.5} concentrations compared to the treeless baseline (S1). The single 6-meter leeward sidewalk tree configuration demonstrated the highest local PM_{2.5} reduction. Tree height exerts a directional aerodynamic control; 10-meter trees significantly enhanced streamwise velocity under parallel flow (up to a 26% increase), thereby improving ventilation, but restricted flow under perpendicular conditions, reducing wind speed by 58%. These findings confirm a dual role where all scenarios yield overall PM_{2.5} reductions, but localized accumulation risks exist due to suppressed ventilation. Optimal PM_{2.5} mitigation requires strategic design, specifically selecting sub-eave tree heights and maintaining adequate canopy clearance, to prioritize beneficial aerodynamic mixing and inform climate-responsive urban planning.

Keywords—street tree, PM_{2.5}, Computational Fluid Dynamics (CFD), urban area

I. INTRODUCTION

Urbanization continues to reshape the world's economic, social, and environmental systems. As cities densify to accommodate rapid population growth, compact urban forms and high-rise developments create deep street canyons that constrain natural ventilation and hinder pollutant dispersion. These morphological characteristics intensify roadside air pollution, a critical public health issue, particularly in rapidly expanding metropolitan regions such as the Bangkok Metropolitan Region (BMR), where Samut Prakan serves as a key industrial-urban hub within the metropolitan air basin. Within such constrained environments, fine particulate matter (PM_{2.5}) concentrations frequently exceed both national and international standards. The World Health Organization [1] reports that approximately 99% of the global population breathes air exceeding safe limits, contributing to nearly seven million premature deaths annually from cardiopulmonary and respiratory diseases. Similarly, Thailand's Pollution Control Department [2] has consistently recorded exceedances of the 24-Hour PM_{2.5} standard (37.5 µg/m³) during the cool season (November-March),

while Samut Prakan recorded no “good air” days under the U.S. Air Quality Index (AQI) threshold (12 µg/m³) in 2023.

Street trees are among the most widely implemented urban-greening measures for mitigating traffic-related particulate pollution. Studies have shown that their effectiveness depends strongly on canopy structure and local wind conditions, which govern aerodynamic mixing and particle deposition [3–5]. However, these interactions remain underexplored in tropical monsoon cities, where seasonal wind reversals may substantially alter pollutant dispersion dynamics. The persistence of hazardous PM_{2.5} levels highlights the urgent need for localized and evidence-based mitigation strategies that reflect Thailand's unique urban morphology and climatic context.

Accordingly, this study aims to evaluate how street-tree configuration and prevailing wind direction jointly influence PM_{2.5} dispersion in a dense urban canyon. Using three-dimensional Computational Fluid Dynamics (CFD) simulations based on the Reynolds-Averaged Navier-Stokes (RANS) model, the research investigates multiple planting configurations under two dominant monsoonal wind regimes (west-perpendicular and south-parallel). The objectives are (1) to examine how wind orientation affects wind velocity in a street canyon with trees, and (2) to assess the influence of different tree-planting configurations on PM_{2.5} reduction and concentration.

Building on prior CFD research on vegetation-pollutant interactions, this study contributes additional evidence in three ways. First, it compares street-tree height (6 m vs 10 m) and planting location (sidewalk versus median strip) under two contrasting wind orientations (parallel and perpendicular), a combination that has been less frequently examined together in CFD-based street-canyon studies. Second, the analysis is situated in a tropical monsoon urban corridor, where the interaction between seasonal wind regimes and vegetation structure has been reported less often than in temperate case studies. Third, the CFD setup is supported by on-site measurements to strengthen confidence that the simulated flow and concentration patterns are representative of real street-canyon conditions. Together, these elements improve understanding of how tree configuration and wind orientation influence near-road PM_{2.5} exposure and provide practical implications for urban greening strategies in tropical cities.

II. LITERATURE REVIEW

Street trees and vegetation barriers are widely recognized

as nature-based solutions for mitigating near-road air pollution. Their effectiveness arises from two principal mechanisms, aerodynamic modulation and particle deposition. Vegetation alters airflow patterns by modifying wind velocity, direction, and turbulence intensity, while particulate matter can be removed through dry deposition and impaction on leaf surfaces. Numerous studies have demonstrated that these combined processes can reduce local PM_{2.5} concentrations, although outcomes vary substantially with vegetation characteristics and urban morphology [6–8].

Leaf Area Density (LAD) is one of the most influential parameters controlling deposition and turbulence. Hong *et al.* [9] reported that PM_{2.5} concentrations declined with increasing LAD, with capture efficiencies reaching 75–85%. Similarly, Jeanjean *et al.* [10] found that roadside trees in Leicester, UK, achieved up to 9% aerodynamic reduction in PM_{2.5} levels. However, vegetation does not universally improve air quality. Excessive canopy density can obstruct natural ventilation and trap pollutants within street canyons. Liu and Zheng [11] found that high canopy density may elevate PM_{2.5} concentrations under stagnant conditions. Consequently, the net impact of street trees depends on a balance between deposition and ventilation, governed by tree height, spacing, porosity, and species-specific LAD characteristics [12, 13].

Wind direction and speed further determine pollutant dispersion and vegetation performance. Wind orientation influences vortex formation within street canyons, thereby controlling vertical exchange and pollutant residence time [14, 15]. Perpendicular winds generally lead to higher PM_{2.5} concentrations than parallel winds because recirculating vortices suppress ventilation efficiency [16, 17]. Tree-induced effects also vary spatially within the canyon; windward trees may increase pollutant concentrations by 9–67%, whereas leeward trees can reduce concentrations by up to 14%, depending on canopy spacing and ambient wind velocity [18–21]. Seasonal variability compounds these dynamics, as monsoonal wind regimes alter prevailing airflow patterns and pollutant transport pathways [22].

In Thailand, urban corridors such as Sukhumvit Road in Samut Prakan characterized the interaction between street geometry, roadside vegetation, and monsoon-driven wind systems. The southwest monsoon (May–October) and northeast monsoon (November–March) produce alternating dominant wind regimes that substantially influence near-surface pollutant behavior. Despite this, relatively few studies have examined how tropical monsoonal winds interact with vegetation structure to affect PM_{2.5} dispersion in dense urban environments. Limited attention to the combined aerodynamic and deposition processes under variable monsoonal conditions represents an important knowledge gap.

Many prior CFD investigations have relied on idealized canyon geometries, steady inflow conditions, or simplified vegetation representations that may not capture site-specific turbulence and dispersion processes in tropical cities. Assumptions of uniform wind profiles and homogeneous canopies often overlook the influence of complex urban morphology and seasonal variability. Moreover, relatively few studies integrate in-situ meteorological and concentration measurements for model calibration and validation, limiting

confidence in CFD predictions under real urban boundary-layer conditions.

Addressing these limitations, this study develops a validated three-dimensional CFD framework incorporating field-observed meteorological data and explicit vegetation representations to examine how tree height, canopy density, and spatial configuration influence PM_{2.5} dispersion under contrasting wind orientations. By situating the analysis within the real-world context of Samut Prakan's mixed-use urban corridor, this research provides context-specific evidence and methodological insight relevant to climate-responsive street design and sustainable urban air-quality management in tropical monsoon environments.

III. MATERIALS AND METHODS

A. Study Area

The study was conducted in Samut Prakan municipality (13°36'01.5"N 100°35'51.6"E) (Fig. 1), a central region of Thailand situated at the mouth of the Chao Phraya River where it flows into the Gulf of Thailand.

As the administrative center of Samut Prakan province, the municipality has undergone rapid urban expansion as a satellite city of Bangkok. This growth has created dense commercial and industrial zones that generate heavy traffic, the primary source of particulate matter in the area. During the past decade, PM_{2.5} concentrations in the municipality have persistently remained above the national standard of 37.5 µg/m³, with peaks observed in January, October, November, and December. The Thai Meteorological Department (TMD) reports an average annual temperature of 28.8 °C, rainfall between 1100–1500 mm, and a mean wind speed of 13.98 km/h, predominantly from the northeast. With a population of 48,622 and a density of 6633 people/km², the municipality exhibits high population concentration.

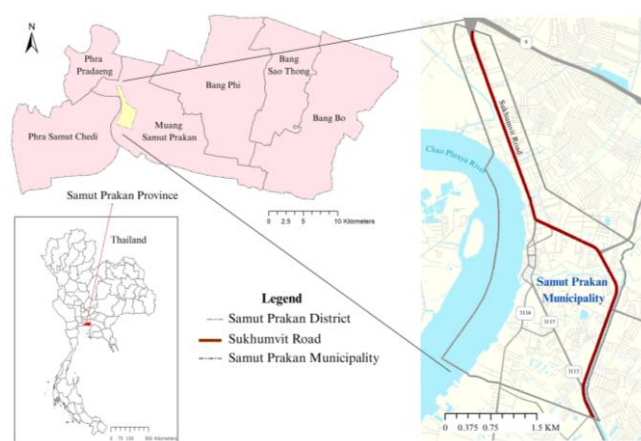


Fig. 1. Sukhumvit Road in Samut Prakan municipality.

This study focuses on Sukhumvit Road, a major 488.4 km arterial route connecting Bangkok with eastern Thailand. The selected 10.5 km segment within Samut Prakan Municipality, between the Bang Na and Praeksa intersections, represents a densely developed urban corridor combining residential, commercial, and industrial uses. Field measurements revealed heavy traffic during morning and evening rush hours, with peak particulate accumulation observed between 13:00 and 15:00. The corridor comprises six traffic lanes, a central median, sidewalks, adjacent buildings, and an elevated transit

line. Street trees occur intermittently along both sides and the median, planted in mixed patterns, some grouped, others isolated, with average heights of 6–10 m.

B. Scenario Setting

The scenario design utilized the study area’s representative road geometry and existing street-tree distribution to develop nine total simulations, varying tree height and planting location. The standardized cross-section comprised six 3.5 m traffic lanes, a 3.5 m median strip, 3.5 m sidewalks, and 2 m building setbacks on both sides. Tree heights of 6 m and 10 m were selected as the local minimum and maximum, consistent with the 5–15 m range recommended by the Royal Forest Department (2022) [23]. Each tree had a standardized 3.5 m canopy width. Trees were strategically placed on the sidewalks and median strip to explore various mitigation strategies. A base-case scenario (no trees) was established as the reference for comparing the eight tree configurations (summarized in Table 1).

Table 1. Street tree configuration categorized by tree height and planting area

| Scenario | Description |
|----------|--|
| 1 | No trees (base case) |
| 2 | Single 6 m tree on the sidewalk |
| 3 | Single 6 m tree on the sidewalk and in the median strip |
| 4 | Single 10 m tree on the sidewalk |
| 5 | Single 10 m tree on the sidewalk and in the median strip |
| 6 | Pair of 6 m trees on the sidewalk |
| 7 | Pair of 6 m trees on the sidewalk and in the median strip |
| 8 | Pair of 10 m trees on the sidewalk |
| 9 | Pair of 10 m trees on the sidewalk and in the median strip |

In addition to variations in tree arrangement, the simulations also considered two prevailing wind directions representative of seasonal monsoonal flow patterns in Samut Prakan. The south wind ($\theta = 0^\circ$) corresponds to flow parallel to the street axis, while the west wind ($\theta = 90^\circ$) corresponds to flow perpendicular to the street canyon. These orientations capture two dominant aerodynamic regimes, channeling flow and skimming flow, that critically influence pollutant dispersion and ventilation efficiency in dense urban corridors. Fig. 2 presents the schematic representation of the two wind-direction scenarios applied in the CFD simulations.

C. Computational Domain and Boundary Conditions

ANSYS Fluent, a general-purpose Computational Fluid Dynamics (CFD) software, was used to simulate airflow and particle dispersion along the road [24]. The computational domain was designed to represent the study area’s geometry, featuring buildings and sidewalks on both sides of a six-lane road. Model dimensions were defined as follows: building height 15 m, sidewalk width 3.5 m, median width 3 m, and lane width 3.5 m. The inlet and outlet boundaries were located vertically above the buildings. Domain extents were set to 5H upstream, 15H downstream, and H above the building height ($H = 15$ m) [25, 26]. Particle inlets, representing vehicular PM2.5 emissions, were positioned at the road center with a cross-section of 0.3×0.3 m. For tree scenarios, the canopy width was standardized at 3.5 m, and the distance between trunks was 6 m, as shown in Fig. 2.

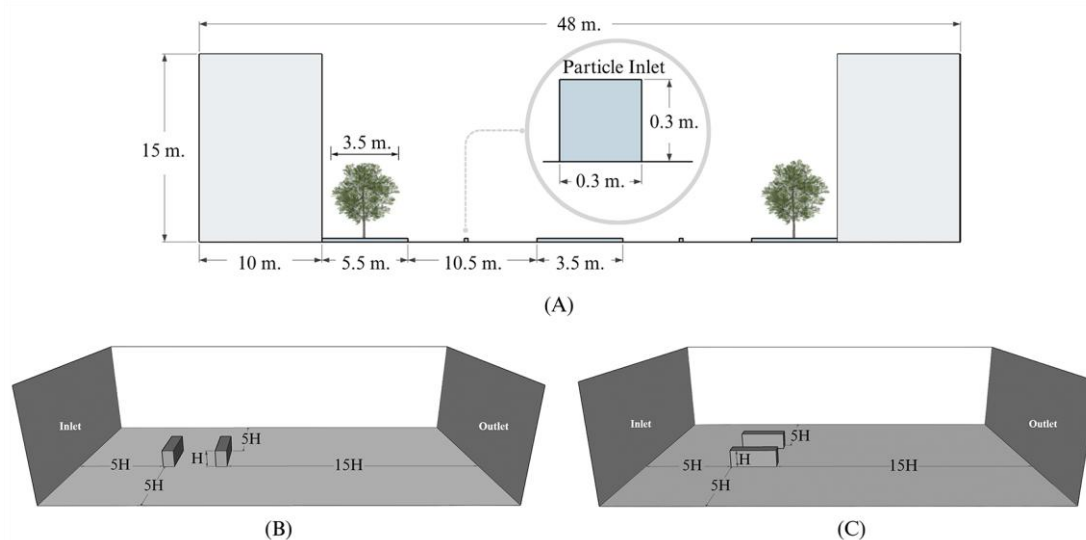


Fig. 2. Model conditions under different wind directions. (A) Cross-sectional geometry of the computational domain, (B) Perpendicular wind, (C) Parallel wind.

The wind velocity was set to 3.878 m/s at a reference height of 11 m, based on data from the TMD, representing the average wind speed in Samut Prakan Province. The incoming wind profile at the domain inlet was defined using the power-law equation.

$$\frac{U(z)}{U_H} = \left(\frac{z}{H}\right)^\alpha \quad (1)$$

where $U(z)$ is the wind velocity (m/s) at height z , $U_H = 3.878$ m/s. is the reference velocity at reference height ($H = 11$ m), and $\alpha = 0.33$ is the ground roughness exponent

representing an urban surface with dense buildings. The inlet velocity vector was adjusted according to the two simulated wind orientations, south-parallel ($\theta = 0^\circ$) and west-perpendicular ($\theta = 90^\circ$).

The outlet boundary was set as a pressure outlet with backflow turbulence intensity equal to that of the inlet. The top boundary was defined as a symmetry plane to permit undisturbed flow development, while all solid surfaces (roadway, facades, roofs, and sidewalks) were modeled as no-slip walls.

The mesh size within the computational domain was gradually increased from 1.2 m to 2.0 m, while a finer mesh size of 0.5 m was applied locally in the tree regions to better resolve vegetation-induced flow effects. Depending on the presence of street trees, the total number of mesh elements ranged from approximately 10.7 to 10.8 million. Mesh quality was evaluated using the element quality metric, yielding an average value of approximately 0.82–0.84. Mesh quality evaluation values ranged from 0 to 1, where values closer to 1 indicate better mesh quality. These results confirm that the mesh resolution and quality were adequate for stable and reliable CFD simulations.

The standard k - ϵ turbulence model was adopted to solve the Reynolds-Averaged Navier-Stokes (RANS) equations, an approach widely validated for microscale urban airflow simulations [18, 22]. The turbulent kinetic energy (k) and dissipation rate (ϵ) were calculated using the following relationships.

$$k = \frac{\mu_*^2}{\sqrt{C_\mu}} \left(1 - \frac{z}{\delta}\right) (\text{m}^2/\text{s}^2) \quad (2)$$

$$\epsilon = \frac{\mu_*^3}{Kz} \left(1 - \frac{z}{\delta}\right) (\text{m}^2/\text{s}^3) \quad (3)$$

where $\mu_* = 0.54$ is the friction velocity (m/s), $C_\mu = 0.09$ is the dimensionless constant, z is the height above ground (m), $\delta = 90$ is the depth of the boundary layer, and $k = 0.4$ is von Karman's constant. All simulations were conducted under steady-state conditions using the RANS to represent time-averaged airflow and PM2.5 dispersion.

In the CFD model, only tree canopies were represented, simplified as cubic porous media [25]. The aerodynamic effects of vegetation were modeled using the Darcy-Forchheimer porous-media formulation implemented in ANSYS Fluent [4, 27], in which vegetation acts as a momentum sink within the Reynolds-Averaged Navier-Stokes equations. Porosity and resistance coefficients were specified directly in the porous-zone settings, with a porosity value of 0.9, a viscous resistance of 2.42×10^5 , and an inertial resistance coefficient (C2) of 0.145.

The porous-zone geometry corresponded to the canopy dimensions used in each scenario, with a plan width of 3.5×3.5 m. Canopy thicknesses of 3 m and 6 m were used to represent the foliage zones of the 6-Meter and 10-Meter trees, respectively. Particulate matter (PM2.5) in this study was assumed to originate from vehicle emissions generated by fuel combustion. The discrete phases model was used to track the motion of particles. The particles were modelled as inert ash solids. Previous studies reported PM2.5 densities ranging from 1 to 3 g/cm³ (1000–3000 kg/m³) [12]. The reduction rate of PM2.5 by trees was calculated using the following equation:

$$\text{Reduction rate} = \frac{\text{Reduction}}{\text{PM2.5 concentration before intervention}} \times 100\% \quad (4)$$

where reduction is the difference between the data before and after the intervention by the tree.

Model validation was carried out using on-site measurements obtained along Sukhumvit Road to ensure that

the CFD simulation accurately represented actual urban microclimatic conditions. Eight fixed monitoring stations were established along the road, strategically positioned on both the windward and leeward sides to capture spatial variability in airflow and PM2.5 distribution. The validation process was conducted under a perpendicular wind condition relative to the street axis. PM2.5 concentration, air temperature, and relative humidity were measured using a CEM DT-9880 real-time particle counter based on laser light-scattering principles, with a reported PM2.5 measurement accuracy of $\pm 5\%$. Wind speed was measured using a hot-wire air velocity meter based on thermal anemometry, with an accuracy of $\pm 3\%$ of reading ± 0.05 m/s. All instruments were factory-calibrated prior to deployment and applied consistently across all monitoring points. Measurements were conducted at pedestrian height (1.5 m) and recorded at 5-Minute intervals between 07:00 and 18:00 during January, corresponding to the typical PM2.5 pollution season in Thailand. The mean of twelve consecutive 5-Minute readings was used to derive hourly representative values for model calibration and validation.

Table 2. Comparison of observed and model results in a paired-sample t-test

| Variable | Mean | STD | <i>t</i> | <i>p</i> |
|---------------------|---------|--------|----------|----------|
| Wind Velocity | -0.0786 | 0.7699 | -0.180 | 0.735 |
| PM2.5 Concentration | 0.0588 | 3.58 | 0.116 | 0.857 |

The agreement between modelled and observed wind velocities and PM2.5 concentrations was statistically assessed using a paired-sample t-test, which evaluates whether systematic differences exist between the two datasets. The test results showed *p*-values greater than 0.05 for both parameters, as shown in Table 2, indicating that discrepancies between simulated and observed values were not statistically significant. The R^2 values for wind velocity and PM2.5 concentration were 0.92 and 0.86, respectively. These results indicate a strong agreement in the trends and variability between the simulated and observed airflow and pollutant concentration patterns under the investigated conditions.

IV. RESULT

A. The Effect of Wind Direction and Street Tree on Wind Velocity

1) Wind velocity under perpendicular wind conditions

The airflow patterns of perpendicular wind ($\theta = 90^\circ$), illustrates in Fig. 3, showing airflow over the building rooftops and the formation of a recirculation zone within the street canyon. In the baseline Scenario 1 (no trees), with average wind velocity at 0.78 m/s, this recirculation occurs on both the windward and leeward sides as the wind reverses direction after impinging on the building facade.

The presence of trees markedly alters this pattern, affecting wind velocity and particulate dispersion. A notable finding is the high-speed flow channeled through narrow gaps between trees and buildings, which intensifies localized wind velocity and modifies the overall airflow structure. Consequently, the average, minimum, and maximum wind velocities at pedestrian level ($Z = 1.5$ m) varied across the tested scenarios.

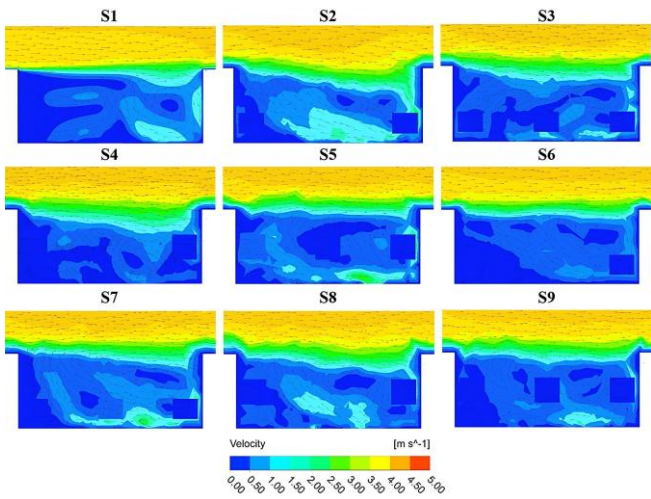


Fig. 3. The wind direction and contour of wind velocity under perpendicular wind at the sampling site, which were affected by trees and buildings.

As shown in Fig. 4, for the 6 m tree scenarios, the presence of trees increased the average wind velocity within the street canyon compared to the treeless baseline (S1). The highest average velocity (1.17 m/s) occurred in Scenario 2 (a single 6-m sidewalk tree), representing a 50% rise over the baseline (0.78 m/s). In contrast, Scenario 6 (a pair of 6 m sidewalk trees) produced the lowest average velocity among tree scenarios, with a 23% increase over S1. For the 10 m tree scenarios, Scenario 5 (a single 10 m tree on the sidewalk and median strip) yielded the highest average velocity (1.34 m/s), a 72% increase relative to S1, while a single 10-m sidewalk tree (S4) generated the lowest. Across all scenarios, maximum wind velocity trends mirrored the averages. The highest minimum velocity occurred in Scenario 8 (0.28 m/s) and the lowest in Scenario 4 (0.15 m/s).

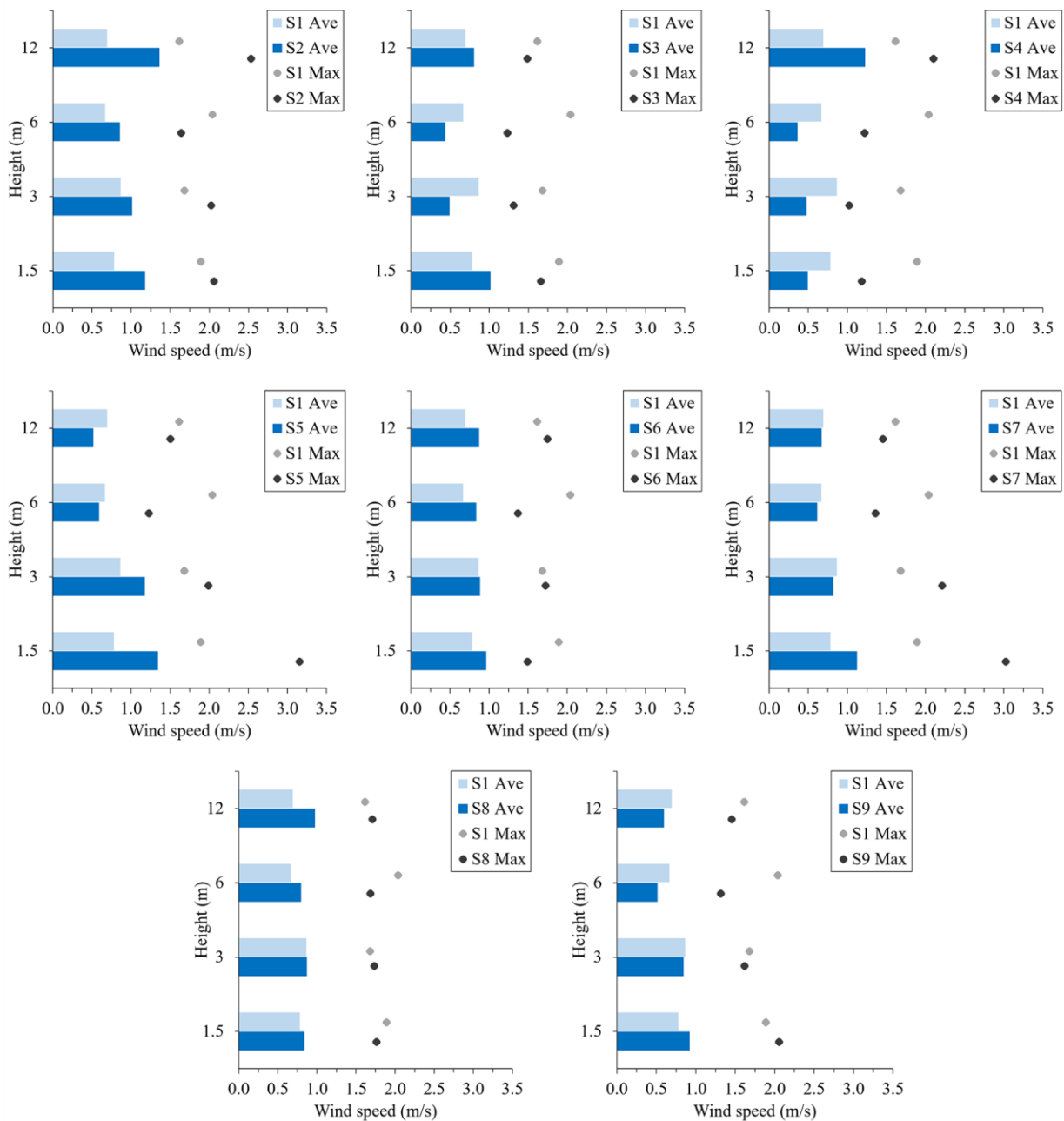


Fig. 4. Wind velocity under perpendicular wind at several heights which were affected by trees.

2) Wind velocity under parallel wind conditions

Under parallel wind conditions ($\theta = 0^\circ$), the airflow is channeled along the street axis, forming a longitudinal flow regime with relatively uniform velocity distribution across the canyon. As shown in Fig. 5, wind vectors primarily align with the road direction, and air movement is guided between the building rows, minimizing large-scale recirculation vortices typically observed under perpendicular inflow. The presence of trees modifies this channeling flow by inducing local shear zones and accelerating near-ground air through constricted spaces between canopies.

As shown in Fig. 6, the baseline scenario (S1), representing a treeless condition, recorded an average velocity of 1.17 m/s, comparable to the perpendicular-wind case. In contrast, most scenarios with tree planting exhibited significantly higher average velocities, reaching up to 2.72 m/s. The highest average velocity occurred in scenario S9 (2.72 m/s), which featured a pair of 10 m trees located on both the sidewalk and the median strip. This configuration produced an approximate 132.5% increase over the treeless baseline. Similarly, scenarios S5 (2.70 m/s) and S3 (2.57 m/s), both incorporating trees along the sidewalk and median strip, demonstrated substantial improvements of 130.8% and 119.7%, respectively. Overall, most tree configurations enhanced air

flow, with average velocity increases exceeding 50%. The only exception was S6, comprising a pair of 6 m trees positioned solely on the sidewalk, which exhibited a slightly lower average velocity of 1.14 m/s, suggesting minimal local flow obstruction.

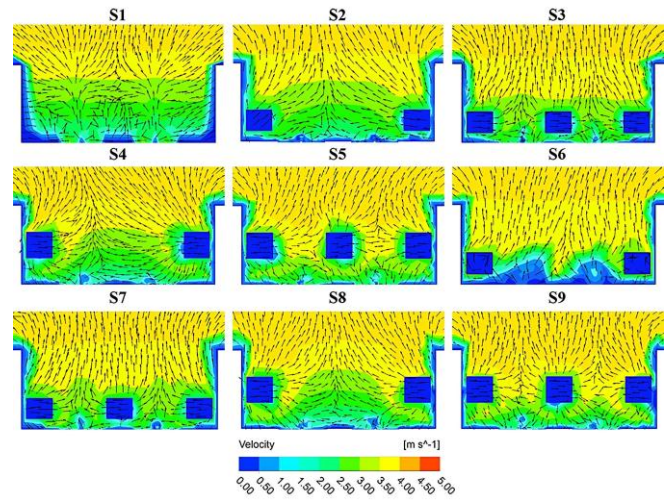


Fig. 5. The wind direction and contour of wind velocity under parallel wind at the sampling site, which were affected by trees and buildings.

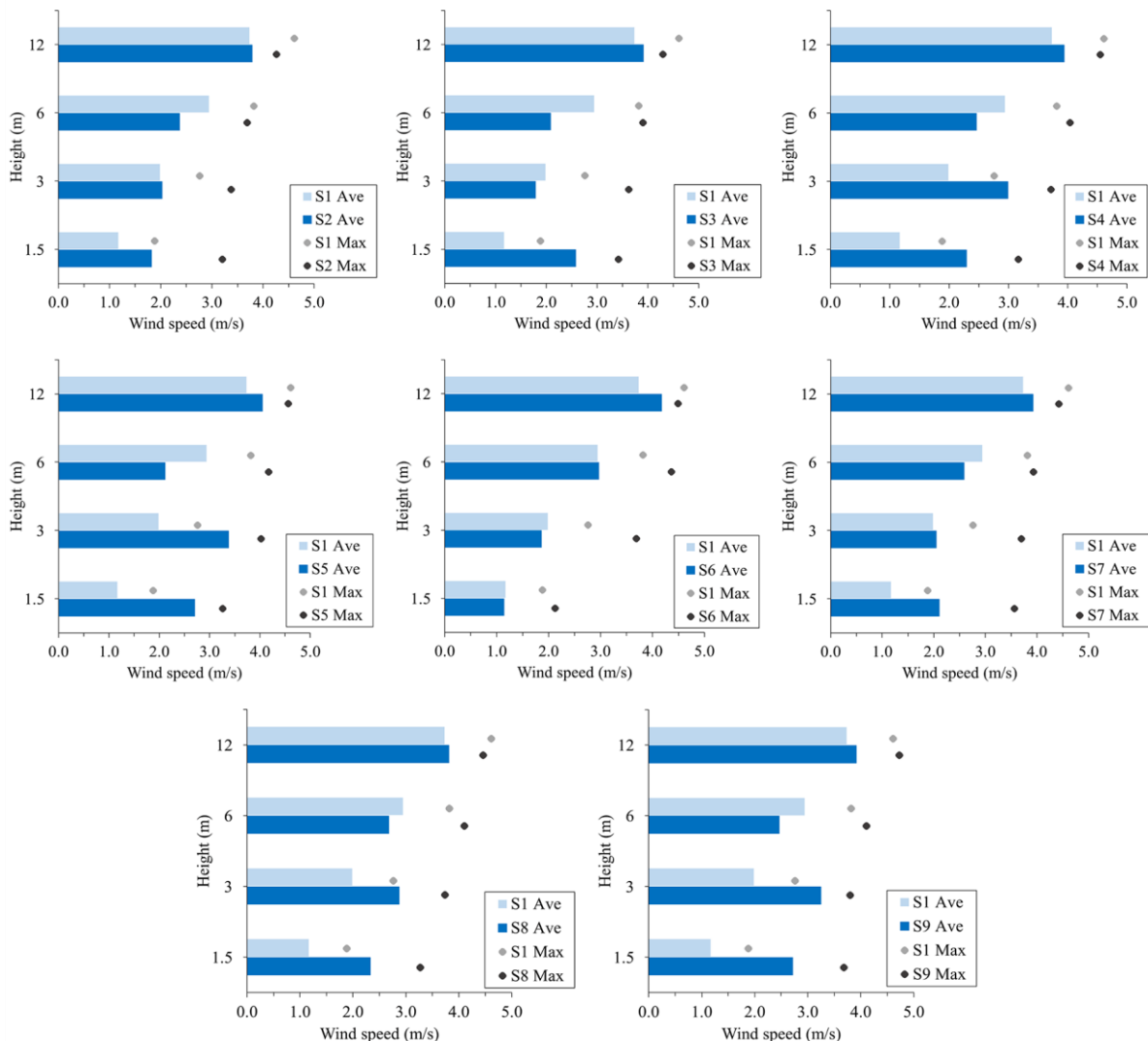


Fig. 6. Wind velocity under parallel wind at several heights which affected by trees.

3) Wind velocity at pedestrian level (1.5 m)

The results indicate that the primary effect of tree planting within the urban street canyon is the attenuation of pedestrian-level wind velocity (1.5 m), a phenomenon consistently observed under both perpendicular and parallel wind directions. In the perpendicular flow scenario, the average wind speed along the leeward sidewalk is distinctly lower than that on the windward side, maintaining a consistently low magnitude across most analyzed cases, typically ranging from 0.18 to 0.60 m/s. These values are notably below the mean wind velocity recorded across the broader study domain. In contrast, under parallel wind flow, the average wind speeds along both the leeward and windward sidewalks are relatively comparable, with velocities on the leeward side ranging from 1.33 to 2.66 m/s, indicating a higher overall velocity magnitude than that observed during parallel flow conditions. Compared to the perpendicular wind condition, as shown in Fig. 7, the parallel wind scenario exhibited notably higher ventilation efficiency.

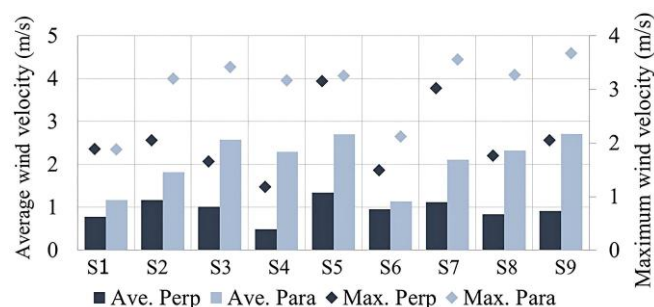


Fig. 7. Comparison of wind velocity under different wind directions. Where Ave. Perp refers to the average PM2.5 concentration under perpendicular wind direction, Ave. Para refers to the average PM2.5 concentration under parallel wind direction, Max. Prep refers to the maximum PM2.5 concentration under perpendicular wind direction, and Max. Para refers to the maximum PM2.5 concentration under parallel wind direction.

4) Influence of tree height

The influence of tree height on wind mitigation exhibits a pronounced dependence on the incident wind direction. Under perpendicular flow conditions, the 10 m trees produced lower average wind velocities along the leeward sidewalk compared to the 6 m trees. This outcome is primarily attributed to the reduced clearance between the ground and the denser canopy of the taller trees, which enhances wind recirculation and promotes localized flow dispersion. Consequently, this configuration resulted in a 58% reduction in pedestrian-level wind velocity, decreasing from 1.17 m/s with 6 m trees (S2) to 0.49 m/s with 10 m trees (S4).

In contrast, under parallel flow conditions, the taller trees (S4) generated higher wind velocities than the 6 m trees (S2), leading to an approximate 26% increase in average velocity, from 1.82 m/s to 2.29 m/s. This result suggests that greater tree height will facilitate longitudinal channeling of the airflow under parallel wind orientation, enhancing through-canyon ventilation.

A. Influence of Tree-Planting Configurations on PM2.5 Dispersion and Reduction

CFD simulations of PM2.5 dispersion along Sukhumvit Road indicate that trees play a dual role in managing urban air quality; they can reduce overall pollutant levels but may

also cause localized accumulation depending on canopy density and placement. As shown in Fig. 8, PM2.5 originates from the road center and is advected toward the sidewalks, accumulating on the leeward side where higher concentrations are evident. Increasing tree density alters local aerodynamics, slowing PM2.5-laden air flow and promoting accumulation. This demonstrates a critical trade-off: while trees intercept pollutants, dense planting can suppress natural dispersion. Leeward vegetation may act as a partial barrier, reducing concentrations in its wake, yet tall or dense crowns can hinder vertical mixing and shift plumes toward building facades, forming localized hotspots. Similar effects have been observed in previous studies [12].

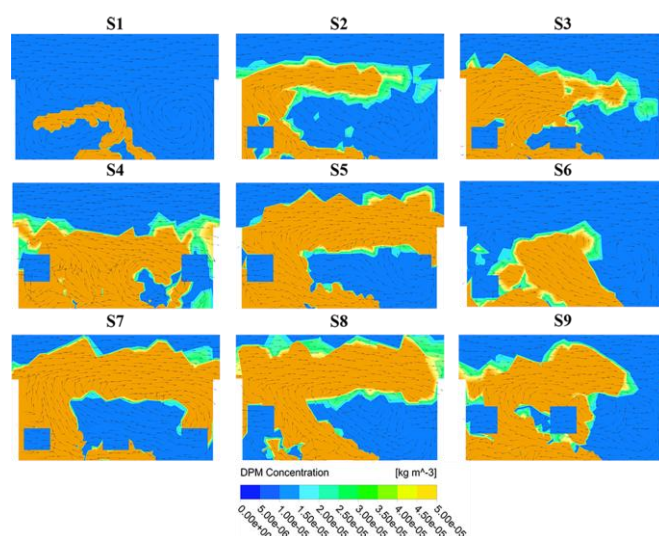


Fig. 8. Simulated PM2.5 concentration fields and flow vectors for S1–S9, showing plume advection toward the leeward sidewalk, aerodynamic damping with denser plantings, and localized reductions due to deposition as air passes through tree canopies.

B. PM2.5 concentrations at pedestrian level (1.5 m)

As shown in Fig. 9, all tree scenarios significantly reduced average pedestrian-level (1.5 m) PM2.5 concentrations compared to the treeless baseline (S1). For 6 m trees, the most effective configuration was a single sidewalk tree (S2), achieving a 61% reduction, while a pair of 6 m trees on the sidewalk and median strip (S7) reduced concentrations by 34%.

For 10 m trees, the optimal setup, a pair on both sidewalk and median strip (S9), produced the highest reduction (62%) and the lowest maximum concentration (61.72 $\mu\text{g}/\text{m}^3$). A single 10 m sidewalk tree (S4) achieved a 52% reduction.

Overall, single-tree planting on the sidewalk was generally more effective than the combined sidewalk median configuration. Notably, a single 6 m tree outperformed the 10 m tree, highlighting the complex interaction among tree height, density, and placement in influencing pollutant mitigation efficiency.

The PM2.5 assessment revealed higher concentrations on the leeward side than on the windward side at the 1.5 m pedestrian level. Leeward concentrations exceeded the standard limit of 37.5 $\mu\text{g}/\text{m}^3$, ranging from 22.5 to 148.6 $\mu\text{g}/\text{m}^3$ (average 81.7 $\mu\text{g}/\text{m}^3$), whereas windward values ranged from 7.99 to 36.9 $\mu\text{g}/\text{m}^3$ (average 21.5 $\mu\text{g}/\text{m}^3$). Planting a single tree on the sidewalk produced the greatest reduction in PM2.5 concentration.

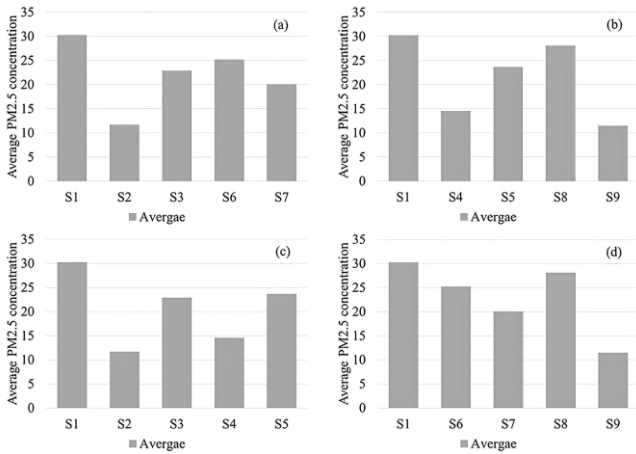


Fig. 9. Average and maximum PM_{2.5} concentration at the pedestrian level (1.5 m): (a) 6-Meter tree comparing with no tree scenario, (b) 10-Meter tree comparing with no tree scenario, (c) A single of 6-meter and 10-Meter tree comparing with no tree scenario, and (d) A pair of 6-meter and 10-Meter tree comparing with no tree scenario.

Fig. 10 illustrates that PM_{2.5} concentrations decrease substantially with height, peaking at the pedestrian level (1.5 m) and declining between 3 and 6 m. Trees effectively reduced PM_{2.5} levels, with the strongest mitigation observed near the canopy height. Among all configurations, a single 6 m tree (S2) resulted in the greatest reduction in PM_{2.5} concentration, approximately 61% at the pedestrian height (1.5 m) and up to 73% at the roof level (12 m), compared with the treeless baseline (S1). This finding suggests that a small tree can provide significant localized filtration without disrupting airflow or promoting pollutant trapping.

A single 10 m tree on the sidewalk and median strip (S5) reduced PM_{2.5} concentrations by about 32% across all heights, less effective than the 6 m tree but still demonstrating notable purification, particularly at the canopy level. Across most tree scenarios, concentrations decreased with height due to enhanced deposition and filtration on canopy surfaces.

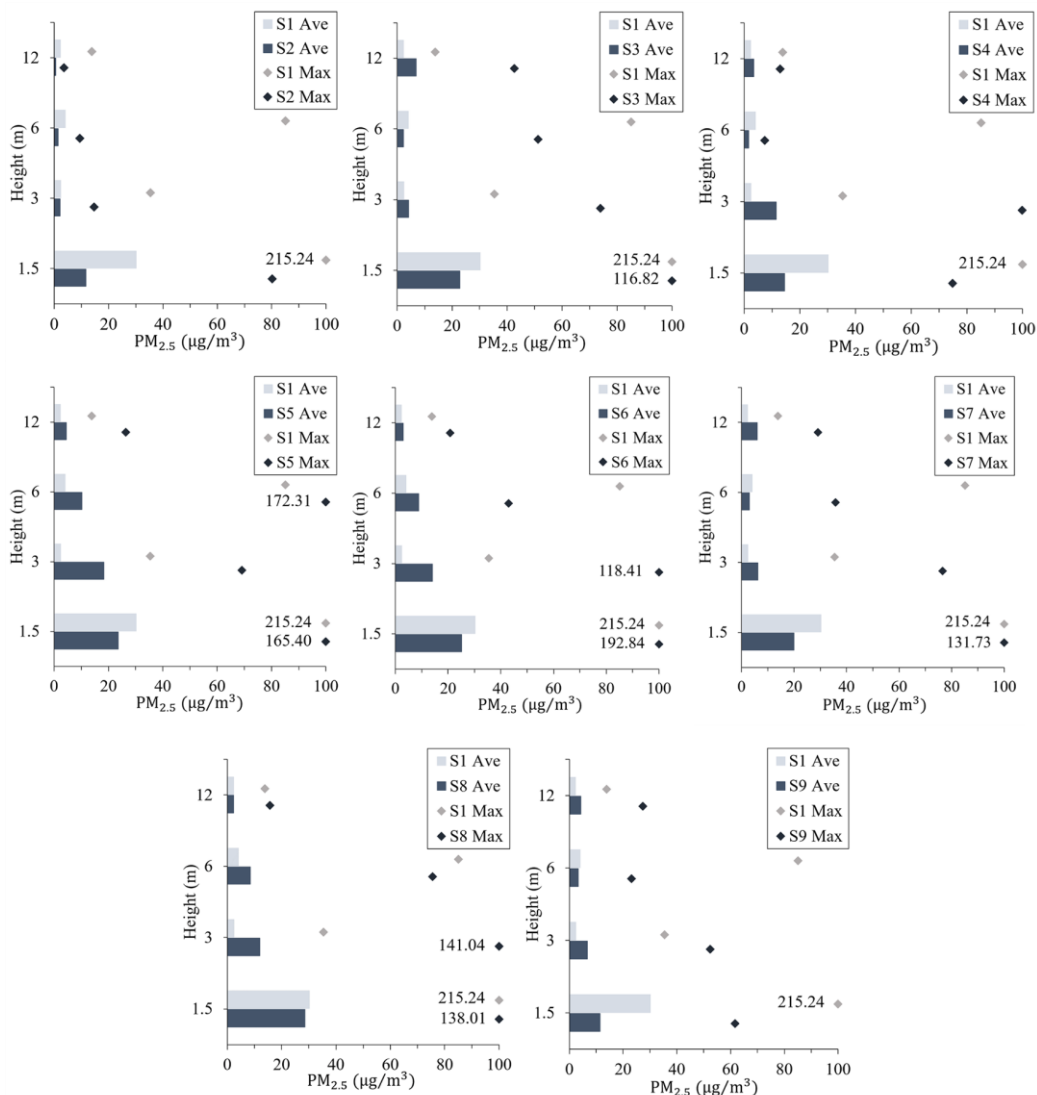


Fig. 10. An average PM_{2.5} concentration at different heights.

V. DISCUSSION

A. Effect of Wind Direction on Wind Velocity and Airflow

The orientation of the incoming wind strongly governs flow kinematics and turbulence generation within urban street

canyons, influencing the development of vortices, shear layers, and recirculation zones that control near-ground ventilation and pollutant dispersion [16, 28]. The simulations under perpendicular (90°) and parallel (0°) wind directions reveal distinct aerodynamic behaviors depending on tree configuration and canopy height.

Under perpendicular inflow, the wind impinges laterally on the building facade, generating a dominant recirculation vortex and limited vertical exchange within the canyon. In the baseline case (S1), the mean velocity (0.32 m/s) reflects the classical single-vortex regime, consistent with the observations of Oke [28] and Santiago *et al.* [29]. The addition of a single 6 m tree (S2) slightly decreases the leeward velocity to 0.26 m/s, as the canopy introduces localized turbulence and partially blocks the downwind flow. When an additional tree is placed on the median strip (S3), aerodynamic interaction between canopies enhances shear production and induces secondary eddies, accelerating the near-ground flow and increasing the average velocity to 0.61 m/s. This suggests that moderate vegetation density and balanced placement promote recirculation-driven momentum exchange, thereby improving airflow within the canyon.

However, the benefits of vegetation are offset when canopy height or density increases. The introduction of taller trees (10 m) in S4 and S5 amplifies drag and reduces clearance beneath the canopy, restricting vertical mixing and enlarging stagnation zones near the pedestrian level. These cases exhibit lower mean velocities (0.18–0.35 m/s), in agreement with previous CFD analyses [23, 24], which showed that excessive canopy density suppresses air exchange between the canyon and the overlying atmosphere. Similarly, in S6, where two 6 m trees are positioned along the sidewalk, overlapping wakes increase aerodynamic resistance and confine recirculation, reducing velocity to 0.19 m/s. Collectively, these results indicate that under perpendicular winds, vegetation functions primarily as a flow barrier, with excessive canopy volume diminishing canyon ventilation efficiency.

In contrast, parallel wind orientation (0°) produces a markedly different flow regime. In the unvegetated canyon (S1), airflow remains largely aligned with the canyon axis, producing quasi-laminar channeling with limited vertical mixing and a mean velocity of 1.17 m/s. Similar streamlined behavior has been reported in wind-tunnel and numerical studies [14, 30], where parallel inflow promotes low-turbulence longitudinal flow. When vegetation is introduced along both the sidewalk and median strip (S3), partial canopy confinement produces a venturi-like effect, intensifying pressure gradients and streamwise acceleration, resulting in the highest recorded velocity (2.57 m/s). This configuration enhances longitudinal momentum and turbulence generation, improving overall canyon ventilation. Comparable findings were reported by Li *et al.* [31], who observed that dual-row tree configurations amplify turbulent kinetic energy and promote longitudinal flow acceleration, contributing to pollutant dilution and thermal comfort.

These results highlight the contrasting aerodynamic roles of vegetation under different wind orientations. Perpendicular winds accentuate canopy drag and flow obstruction, whereas parallel winds reveal the potential of strategic tree arrangements to enhance streamwise airflow through controlled aerodynamic interaction. This underscores that vegetation design, particularly canopy height, density, and spatial configuration, should be harmonized with prevailing wind orientation to optimize canyon-scale ventilation and pollutant dispersion [31, 32].

B. Influence of Tree-Planting Configurations on PM_{2.5} Dispersion and Reduction

Tree-planting configuration plays a decisive role in determining the spatial distribution and magnitude of PM_{2.5} concentrations within urban street canyons. This study investigates how optimized vegetation layouts along Sukhumvit Road modulate PM_{2.5} accumulation and aerodynamic redistribution through the analysis of coupled wind fields and concentration patterns.

The results show that vegetation alters wind speed, direction, and pollutant transport, reducing average PM_{2.5} across the canyon while potentially increasing concentrations locally where ventilation is suppressed. This dual effect reflects the aerodynamic and deposition roles of urban vegetation [33–35]. Under traffic emissions, canyon recirculation drives pollutants from the roadway toward the leeward sidewalk, producing a distinct windward-leeward asymmetry in near-ground concentrations [23]. The findings indicate that sidewalk trees can, in some configurations, elevate PM_{2.5} locally by reducing near-surface wind velocity and redirecting flow. Accumulation on the leeward side is governed by a primary vortex, as descending flow from the rooftop impinges on the windward facade and carries pollutants across the road, where they recirculate beneath the canopy, concentrating near facade-tree gaps. Similar behavior has been reported in previous studies. Jeanjean *et al.* [10] observed reduced dispersion under low wind (1 m/s), and Wang *et al.* [8] demonstrated that tree structures hinder canyon ventilation and elevate pollutant levels.

Trees mitigate PM_{2.5} concentrations through two primary mechanisms. The first is aerodynamic enhancement, whereby downwash jets and under-canopy flows accelerate air movement through façade-crown gaps and along the windward clearance, improving local ventilation and pollutant dilution. The second is particle deposition, where foliage acts as a porous medium that captures fine particles through dry deposition as the plume passes through the canopy, particularly along the leeward side [3, 36]. In this study, single 6 m and 10 m trees on the leeward sidewalk produced the greatest reductions in pedestrian-level PM_{2.5}, while sidewalk and combined sidewalk–median plantings achieved broader, though less localized, improvements. Consistent with findings from Wuhan, strategically distributed vegetation enhances air-purification capacity and contributes to improved urban air quality and livability [37].

Canopy height and density strongly influence these effects. Six-meter trees, positioned below eave level, preserved ventilation corridors within the canyon, whereas taller 10 m trees intersected the rooftop shear layer, increasing drag and confining recirculation. Dense or tall tree arrays further elevated aerodynamic resistance, sealing the canyon and worsening near-ground air quality, a pattern also noted by Liu and Zheng [11]. In contrast, low-level vegetation such as shrubs efficiently intercepted near-road plumes while inducing minimal disruption to airflow [20]. Maintaining crowns below the roofline, ensuring under-canopy clearance, and managing canopy porosity through species selection and pruning can therefore balance deposition efficiency with aerodynamic performance.

Street and building orientation relative to prevailing winds

further modulate PM_{2.5} dispersion [38]. Previous studies indicate that deposition plays a secondary role to aerodynamic processes in governing near-road concentrations [24, 36]. Along Sukhumvit Road, which lies nearly perpendicular to the dominant wind, skimming flow over rooftops and strong canyon recirculation restrict pollutant removal [15, 39]. Under this regime, particles become trapped within the vortex, elevating ground-level concentrations [14]. These dynamics underscore the need to consider aerodynamic alignment in tree placement. Where feasible, street segments oriented parallel to prevailing winds can enhance inflow and pollutant exchange [16, 21, 25, 40], supporting more effective canyon ventilation.

Despite the robust comparative trends observed, some limitations should be acknowledged. The airflow and PM_{2.5} dispersion were simulated using a steady-state Reynolds-Averaged Navier-Stokes (RANS) approach, which yields time-averaged flow fields and does not explicitly resolve transient turbulence structures. Street trees were idealized as porous media representing bulk aerodynamic effects, and PM_{2.5} was treated as a single particulate species under steady meteorological conditions without accounting for humidity-dependent hygroscopic growth. These assumptions are consistent with standard urban Computational Fluid Dynamics (CFD) practice and should be considered when interpreting absolute concentration values.

In addition, consistency between field observations and the steady-state modeling framework was ensured by averaging 5-Minute measurements to hourly values. While this temporal aggregation reduces short-term variability, it retains the spatial contrasts in airflow and PM_{2.5} concentrations across monitoring locations, which are directly comparable with steady-state CFD outputs.

Overall, the findings reinforce the principle of “the right trees in the right streets.” In compact urban canyons, this entails selecting sub-eave tree heights, avoiding excessive canopy density, maintaining facade-tree gaps and under-canopy clearance, and using median plantings strategically to disrupt vortices without over-thickening the porous layer. Such configurations enhance both aerodynamic mixing and pollutant deposition, reducing pedestrian-level PM_{2.5} while minimizing the formation of localized hotspots [41, 42].

VI. CONCLUSION

This study demonstrates how aerodynamic behavior and pollutant dispersion in tropical urban canyons are jointly governed by wind orientation and vegetation structure. Through validated CFD simulations, the research clarifies that tree configuration determines whether vegetation enhances or hinders canyon ventilation. Rather than focusing solely on absolute reductions in PM_{2.5}, the findings reveal that the balance between aerodynamic mixing and deposition processes dictates air-quality outcomes. The study advances understanding of how tropical monsoonal winds interact with urban vegetation, emphasizing that tree design should align with local airflow regimes. Appropriate tree height, spacing, and placement can strengthen natural ventilation while maintaining filtration capacity. These insights move beyond site-specific results to provide a transferable framework for designing greener and healthier urban corridors in rapidly

growing tropical cities.

Future applications should extend this modeling approach to evaluate seasonal wind reversals, species-specific canopy effects, and multi-street networks to support integrative, climate-responsive urban planning.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

W.K. conducted the research, performed data analysis, and prepared the final manuscript. A.J. provided guidance on the CFD methodology and contributed to data provision. K.S. assisted in data analysis and manuscript drafting. All authors read and approved the final manuscript. All authors have read and approved the final version of the manuscript.

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REFERENCES

- [1] World Health Organization, *WHO Global Air Quality Guidelines: Particulate Matter (PM_{2.5} and PM₁₀), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide*. Geneva: World Health Organization, 2021.
- [2] Pollution Control Department (PCD), *Thailand Air Quality Report 2023*. Bangkok: Ministry of Natural Resources and Environment, 2023.
- [3] Y. Huang *et al.*, “A review of strategies for mitigating roadside air pollution in urban street canyons,” *Environmental Pollution*, vol. 280, 116971, Mar. 2021. doi: 10.1016/j.envpol.2021.116971
- [4] R. Buccolieri, J. L. Santiago, E. Rivas, and B. Sanchez, “Review on urban tree modelling in CFD simulations: Aerodynamic, deposition and thermal effects,” *Urban Forestry & Urban Greening*, vol. 31, pp. 212–220, Apr. 2018. doi: 10.1016/j.ufug.2018.03.003
- [5] A. Wania, M. Bruse, N. Blond, and C. Weber, “Analysing the influence of different street vegetation on traffic-induced particle dispersion using microscale simulations,” *Journal of Environmental Management*, vol. 94, no. 1, pp. 91–101, Feb. 2012. doi: 10.1016/j.jenvman.2011.06.036
- [6] K. P. Beckett, P. H. Freer-Smith, and G. Taylor, “Urban woodlands: Their role in reducing the effects of particulate pollution,” *Environmental Pollution*, vol. 99, no. 3, pp. 347–360, 1998. doi: 10.1016/s0269-7491(98)00116-5
- [7] X. Lin, M. Chamecki, and X. Yu, “Aerodynamic and deposition effects of street trees on PM_{2.5} concentration: From street to neighborhood scale,” *Building and Environment*, vol. 185, 107291, Nov. 2020. doi: 10.1016/j.buildenv.2020.107291
- [8] L. Wang, J. Su, Z. Gu, and Q. Shui, “Effect of street-canyon shape and tree layout on pollutant diffusion under real tree model,” *Sustainability*, vol. 12, 2105, Mar. 2020. doi: 10.3390/su12052105
- [9] H. Qin, B. Hong, B. Huang, X. Cui, and T. Zhang, “How dynamic growth of avenue trees affects particulate matter dispersion: CFD simulations in street canyons,” *Sustainable Cities and Society*, vol. 61, 102331, Oct. 2020. doi: 10.1016/j.scs.2020.102331
- [10] A. P. R. Jeanjean, P. S. Monks, and R. J. Leigh, “Modelling the effectiveness of urban trees and grass on PM_{2.5} reduction via dispersion and deposition at a city scale,” *Atmospheric Environment*, vol. 147, pp. 1–10, Dec. 2016. doi: 10.1016/j.atmosenv.2016.09.033
- [11] J. Liu and B. Zheng, “A simulation study on the influence of street tree configuration on fine particulate matter (PM_{2.5}) concentration in street canyons,” *Forests*, vol. 14, no. 8, 1550, Jul. 2023. doi: 10.3390/f14081550
- [12] N. R. Jeong, S. W. Han, and B. Ko, “Effects of green network management of urban street trees on airborne particulate matter (PM_{2.5}) concentration,” *International Journal of Environmental Research and Public Health*, vol. 20, no. 3, 2507, Jan. 2023. doi: 10.3390/ijerph20032507
- [13] Y. Chen, X. Ke, M. Min, Y. Zhang, Y. Dai, and L. Tang, “Do we need more urban green space to alleviate PM_{2.5} pollution? A case study in Wuhan, China,” *Land*, vol. 11, no. 6, 776, May 2022. doi: 10.3390/land11060776

- [14] L. Soulhac and P. Salizzoni, "Dispersion in a street canyon for a wind direction parallel to the street axis," *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 98, no. 12, pp. 903–910, Dec. 2010. doi: 10.1016/j.jweia.2010.09.004
- [15] W. Lv, Y. Wu, and J. Zang, "A review on the dispersion and distribution characteristics of pollutants in street canyons and improvement measures," *Energies*, vol. 14, no. 19, 6155, Sep. 2021. doi: 10.3390/en14196155
- [16] J. Pan and J. Ji, "Influence of building height variation on air pollution dispersion in different wind directions: A numerical simulation study," *Applied Sciences*, vol. 14, no. 3, 979, Jan. 2024. doi: 10.3390/app14030979
- [17] Y.-D. Huang, R.-W. Hou, Z.-Y. Liu, Y. Song, P.-Y. Cui, and C.-N. Kim, "Effects of wind direction on the airflow and pollutant dispersion inside a long street canyon," *Aerosol and Air Quality Research*, vol. 19, no. 5, pp. 1152–1171, 2019. doi: 10.4209/aaqr.2018.09.0344
- [18] B. Hong, H. Qin, R. Jiang, M. Xu, and J. Niu, "How outdoor trees affect indoor particulate matter dispersion: CFD simulations in a naturally ventilated auditorium," *International Journal of Environmental Research and Public Health*, vol. 15, no. 12, 2862, 2018. doi: 10.3390/ijerph15122862
- [19] Y. F. Tang, Y. B. Wen, H. Chen, Z. C. Tan, Y. H. Yao, and F. Y. Zhao, "Airflow mitigation and pollutant purification in an idealized urban street canyon with wind driven natural ventilation: cooperating and opposing effects of roadside tree plantings and non-uniform building heights," *Sustainable Cities and Society*, vol. 92, 104483, 2023. doi: 10.1016/j.scs.2023.104483
- [20] A. P. R. Jeanjean, R. Buccolieri, J. Eddy, P. S. Monks, and R. J. Leigh, "Air quality affected by trees in real street canyons: The case of Marylebone neighbourhood in central London," *Urban Forestry & Urban Greening*, vol. 22, pp. 41–53, Mar. 2017. doi: 10.1016/j.ufug.2017.01.009
- [21] R. Buccolieri, C. Gromke, S. Di Sabatino, and B. Ruck, "Aerodynamic effects of trees on pollutant concentration in street canyons," *Science of the Total Environment*, vol. 407, no. 19, pp. 5247–5256, 2009. doi: 10.1016/j.scitotenv.2009.06.016
- [22] J. Xiong, H. Wang, Y. Zhang, Y. Zhao, and Q. Zhang, "City wind impact on air pollution control for urban planning with different time-scale considerations: A case study in Chengdu, China," *Atmosphere*, vol. 14, no. 7, 1068, 2023.
- [23] Royal Forest Department. Suitable tree species for street planting. [Online]. Available: <https://www.forest.go.th/reforest/category/articles/> (in Thai)
- [24] ANSYS, Inc. (2009). *ANSYS Fluent 12.0 Theory Guide*. [Online]. Available: https://www.afs.enea.it/project/neptunius/docs/fluent/html/th/main_pre.htm
- [25] X. Guo, Z. Gao, R. Buccolieri, M. Zhang, and J. Shen, "Effect of greening on pollutant dispersion and ventilation at urban street intersections," *Building and Environment*, vol. 203, 108075, 2021.
- [26] Y. Tominaga *et al.*, "AIJ guidelines for practical applications of CFD to pedestrian wind environment around buildings," *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 96, no. 10–11, pp. 1749–1761, 2008.
- [27] A. O. Mahgoub and S. Ghani, "Numerical and experimental investigation of utilizing the porous media model for windbreaks CFD simulation," *Sustainable Cities and Society*, vol. 65, 102648, 2021.
- [28] T. R. Oke, "Street design and urban canopy layer climate," *Energy and Buildings*, vol. 11, no. 1–3, pp. 103–113, 1988.
- [29] J. L. Santiago, R. Buccolieri, E. Rivas, and F. Martin, "Impact of trees on the dispersion of pollutants in street canyons: CFD modelling insights," *Science of the Total Environment*, vol. 584–585, pp. 458–470, 2017.
- [30] X. Xie, Z. Huang, J. S. Wang, and Z. Xie, "The impact of building configuration on air quality in street canyon," *Atmospheric Environment*, vol. 39, no. 25, pp. 4519–4530, 2005.
- [31] X. Li, Y. Li, and Y. Zhang, "Effects of tree configurations on urban canyon ventilation and pollutant removal: A numerical investigation," *Building and Environment*, vol. 190, 107542, 2021.
- [32] S. Sodoudi, H. Zhang, X. Chi, F. Müller, and H. Li, "The influence of spatial configuration of green areas on microclimate and thermal comfort," *Urban Forestry & Urban Greening*, vol. 34, pp. 85–96, Aug. 2018. doi: 10.1016/j.ufug.2018.06.002
- [33] C. Gromke and B. Ruck, "Pollutant dispersion in urban street canyons with vegetation: CFD simulation of idealised and realistic scenarios," *Atmospheric Environment*, vol. 46, pp. 350–357, 2012.
- [34] A. Wania, M. Bruse, N. Blond, and C. Weber, "Analysing the influence of different street vegetation on traffic-induced particle dispersion using microscale simulations," *Journal of Environmental Management*, vol. 94, no. 1, pp. 91–101, Feb. 2012. doi: 10.1016/j.jenvman.2011.06.036
- [35] Y. Xing and P. Brimblecombe, "Role of vegetation in deposition and dispersion of air pollution in urban parks," *Atmospheric Environment*, vol. 201, pp. 73–83, Mar. 2019. doi: 10.1016/j.atmosenv.2018.12.027
- [36] S. Janhall, "Review on urban vegetation and particle air pollution – Deposition and dispersion," *Atmospheric Environment*, vol. 105, pp. 130–137, Mar. 2015. doi: 10.1016/j.atmosenv.2015.01.052
- [37] Y. Chen, X. Ke, M. Min, Y. Zhang, Y. Dai, and L. Tang, "Do we need more urban green space to alleviate PM2.5 pollution? A case study in Wuhan, China," *Land*, vol. 11, no. 6, 776, 2022.
- [38] Y. Huang, R. Hou, Z. Liu, Y. Song, P. Cui, and C. Kim, "Effects of wind direction on the airflow and pollutant dispersion inside a long street canyon," *Aerosol and Air Quality Research*, vol. 19, no. 5, pp. 1152–1171, 2019.
- [39] S. Vardoulakis, B. E. A. Fisher, K. Pericleous, and N. Gonzalez-Flesca, "Modelling air quality in street canyons: A review," *Atmospheric Environment*, vol. 37, no. 2, pp. 155–182, 2003.
- [40] Q. Li, J. Liang, Q. Wang, Y. Chen, H. Yang, H. Ling, Z. Luo, and J. Hang, "Numerical investigations of urban pollutant dispersion and building intake fraction with various 3D building configurations and tree plantings," *International Journal of Environmental Research and Public Health*, vol. 19, no. 6, 3524, 2022. doi: 10.3390/ijerph19063524
- [41] J. Liu, B. Zheng, Y. Xiang, and J. Fan, "The impact of street tree height on PM2.5 concentration in street canyons: A simulation study," *Sustainability*, vol. 14, no. 19, 12378, 2022. doi: 10.3390/su141912378
- [42] J. Shen, P. Cui, Y. Huang, Y. Wu, Y. Luo, C. H. Sin, and J. Guan, "New insights on precise regulation of pollutant distribution inside a street canyon by different vegetation planting patterns," *Environmental Science and Pollution Research*, vol. 30, no. 22, pp. 63148–63174, 2023. doi: 10.1007/s11356-023-26370-1

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