



Article Effects of Fences and Green Zones on the Air Flow and PM_{2.5} Concentration around a School in a Building-Congested District

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Abstract: We investigated the effects of wall- and tree-type fences on the airflow and fine particular matter (PM_{2.5}) concentration around a school using a computational fluid dynamics (CFD) model. First, we validated the simulated wind speeds and PM_{2.5} concentrations against measured values, and the results satisfied the recommended criteria of the statistical validation indices used. Then, we evaluated the fence effects for 16 inflow directions by conducting numerical simulations with different fence types and heights. With east–southeasterly inflow, relatively high PM_{2.5} from the road was transported to the school. However, the wall-type fence prevented the PM_{2.5} from the road from entering the school, and the PM_{2.5} concentration decreased significantly downwind of the fence. With east–northeasterly inflow, the horizontal wind speed decreased due to the drag caused by the tree-type fence, resulting in a shift in the flow convergence region. The PM_{2.5} concentration decreased in the region of strengthened upward flow. This occurred because the number of pollutants transported from the background decreased. A comparison of the two fence types revealed that the effect of the tree-type fence on inbound pollutants was more significant, due to increased upward flows, than the effect of the wall-type fence.

Keywords: urban area; flows around buildings; fine particulate matter (PM_{2.5}) concentration; fence effects; CFD model

1. Introduction

Compared to coarse atmospheric particles, which are readily filtered by nose hairs and mucous membranes, fine particulate matter ($PM_{2.5}$) infiltrates the blood vessels and is distributed throughout the body, causing complex inflammatory reactions and possibly cardiovascular events [1]. Because of its direct impacts on human health, $PM_{2.5}$ has been estimated to be the largest environmental health risk in Europe [2]. Moreover, the International Agency for Research on Cancer of the World Health Organization has classified $PM_{2.5}$ as a human carcinogen [3].

Many studies have shown that the outdoor air pollution associated with road emissions affects indoor air quality [4–6]. The road emissions from vehicles could contribute a large proportion of the $PM_{2.5}$ concentration in schools, even at low background concentrations [6]. Chemical analyses have revealed that road emissions are the main source of such $PM_{2.5}$, with an estimated contribution to indoor $PM_{2.5}$ concentration of 26.3% [5].

Investigations of outdoor air quality with road emissions and the relevant policies can contribute to improving indoor air quality. In South Korea, it is important to investigate



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). the impacts of road emissions on the air quality in schools because most schools are located near roads in building-congested districts and are exposed to environments affected by road emissions. Fences and trees are the major objects that affect the airflow and air quality around roads [7,8], and the air quality in a school with fences and tree is affected by changes in airflow and pollutant dispersion. Wind speed reduction depends on the location of the fence and the wind direction, and is greater when the distance between the fence and the building is smaller [9]. Moreover, wind speed is reduced when incoming horizontal airflow passes through trees [7]. The pollutant concentration increases in front of the trees but decreases beyond the trees [8]. However, the effects of fences and trees at points around a school on the transport of traffic pollutants are not well studied.

Computational fluid dynamics (CFD) models have been widely used because of their advantage of facilitating a detailed analysis of urban airflow and pollutant dispersion [10–13]. A CFD model can simulate more complex flows and reactive or nonreactive pollutant dispersion in urban areas through its coupling with mesoscale [14,15] chemical models [16,17]. Although CFD models are limited by computing resources, they are suitable for analyses of the effects of fences and trees because they use a high-resolution grid system (~20 m) and coordinate system that can account for obstacles such as buildings [9,13,18].

This study numerically investigated the effects of wall- and tree-type fences on airflow and $PM_{2.5}$ concentration around a school, focusing on the outdoor air quality. We first validated the CFD model against measured wind speeds, wind directions, and $PM_{2.5}$ concentrations at the school. Then, we analyzed the effects of constructing fences and planting trees on airflow and $PM_{2.5}$ concentration by running simulations with and without fences or trees for 16 inflow directions.

2. Numerical Model and Simulation Setup

2.1. CFD Model

We used a Eulerian CFD model incorporating a tree drag parameterization scheme [7,19]. The CFD model includes the momentum equation, mass conservation equation, and transport equation of pollutants. To parameterize subgrid-scale turbulence, the CFD model employs the prognostic equations of turbulent kinetic energy (TKE) and TKE dissipation rate. This model solves the Reynolds-averaged Navier–Stokes (RANS) equations assuming a three-dimensional, nonrotating, nonhydrostatic, and incompressible flow. A staggered grid system with a finite volume method and the semi-implicit method for pressure-linked equations (SIMPLE) algorithm [20] were adopted for the model. Wall functions suggested by Versteeg and Malalasekera [21] were implemented to model the effects of the turbulent boundary layer. To parameterize the tree drag effect, tree drag terms (Equations (1)–(3)) were added into the equations of momentum, TKE, and TKE dissipation rate (ε):

$$F_{tree,i} = -\rho \cdot n_c^3 \cdot C_d \cdot LAD \cdot U_i \cdot |U|, \qquad (1)$$

$$F_{tree,k} = n_c^3 \cdot C_d \cdot LAD \cdot |U|^3 - 4 \cdot n_c^3 \cdot C_d \cdot k \cdot |U|,$$
⁽²⁾

$$F_{tree,\varepsilon} = \frac{3}{2} \cdot \frac{\varepsilon}{k} \cdot n_c^3 \cdot C_d \cdot LAD \cdot |U|^3 - 6 \cdot n_c^3 \cdot C_d \cdot \varepsilon \cdot |U|, \qquad (3)$$

where U_i are the *i*th Cartesian coordinates (i = 1, 2, 3) of the *i*th mean velocity component, and ρ , k, ε , and |U| are the air density, TKE, TKE dissipation rate, and wind speed, respectively. *LAD*, n_c , and C_d indicate the fraction of the area covered by the vertical projection of leaves, leaf area density, and drag coefficient, respectively. For further details, see Kang et al. [7,19].

2.2. Simulation Setup

To investigate the effects of wall- and tree-type fences on airflow and $PM_{2.5}$ concentration, we selected a building-congested district that included a school with fences as the target area (Figure 1a). This study focused on the area around the school, where many trees are planted along the school boundary, so the effect of trees could be modeled well. To realistically model the topography, buildings, and roads, we used geographic information system (GIS) data with a horizontal resolution of 1×1 m. The domain sizes (cell numbers) in the x, y, and z directions were $600 \times 600 \times 300$ m ($300 \times 300 \times 150$), respectively. The grid intervals in all directions were 2 m.



Figure 1. (a) Satellite image, (b) fence location, and (c) computational configurations of the target area.

The wall-type fence was along the school boundary, and the trees were within the wall-type fence (Figure 1b,c). The heights of trees were set to 2 m and 4 m (Table 1). The CNTL case was conducted with no fence around the school. Others were conducted with wall-type (W) or tree-type (T) fences. 2M and 4M stand for 2-m and 4-m fences, respectively. The porosity of the wall-type fence was set to 0%. For the tree-type fence, we set n_c , LAD, and C_d to 1.0, 3.33 (medium-density trees), and 0.2, respectively [7,10]. The vertical profiles of wind, TKE, and TKE dissipation rate (ε) were set following Castro and Apsley [22] as follows:

$$U(z) = \frac{U_*}{\kappa} ln\left(\frac{z}{z_0}\right) cos\theta,\tag{4}$$

$$V(z) = \frac{U_*}{\kappa} ln\left(\frac{z}{z_0}\right) sin\theta,\tag{5}$$

$$W(z) = 0, (6)$$

$$k(z) = \frac{1}{C_{\mu}^{1/2}} U_*^2 \left(1 - \frac{z}{\delta}\right)^2,\tag{7}$$

$$\varepsilon(z) = \frac{C_{\mu}^{3/4} k^{3/2}}{\kappa z},$$
(8)

where U_* is the friction velocity, δ is the boundary-layer depth (1000 m), κ is the von Kármán constant (0.4), and C_{μ} is an empirical constant (0.09) in the RNG *k*– ε turbulence closure scheme.

Table 1. Summary of the fence heights considered in this study.

	Wall Height	Tree Height
CNTL	0 m	0 m
W2M	2 m	0 m
W4M	4 m	0 m
T2M	0 m	2 m
T4M	0 m	4 m

The numerical simulations were performed for 16 inflow directions for each fence configuration summarized in Table 1. The reference wind speed was determined from the average wind speeds measured at the ASOS 159 (69.5 m above sea level) from 2011 to

2020 (Table 2). The background $PM_{2.5}$ concentrations for the 16 directions were determined by the $PM_{2.5}$ concentrations measured at the AQMS 221112 from 2015 to 2020 ($PM_{2.5}$ measurements in South Korea began in 2015). The AQMS 221112 is located 820 m east of the target area. We assumed that the background $PM_{2.5}$ was well mixed within the model domain height and the $PM_{2.5}$ concentrations at the model boundaries were constant with height. To estimate a road emission rate of $PM_{2.5}$, we used the CAPSS (Clean Air Policy Support System) established by the Ministry of Environment, South Korea. We allocated the $PM_{2.5}$ emission rate at each road using the monthly, daily, and hourly emission factors [23] based on the total amount of $PM_{2.5}$ mobile emission of the target area in the CAPSS. The emission rate, *E* in kg m⁻² h⁻¹, was estimated by the top-down emission inventory method [24] as follows:

$$E = \frac{E_d}{A_r} \times EF_m \times EF_d \times EF_h, \tag{9}$$

were E_d and A_r indicate the daily mean PM_{2.5} emission rate (kg day⁻¹) and the total area of roads in the target area, respectively. EF_m , EF_d , and EF_h indicate the monthly, daily and hourly allocation coefficients, respectively. The emission rate on the road in the target area was 2.9×10^{-6} kg m⁻² h⁻¹. In the simulations, PM_{2.5} is emitted from the source at 1 m above the ground (Figure 1b). Because the target area is small, the production and/or reduction of PM_{2.5} in the atmosphere by chemical and physical processes were ignored in this study. The turbulent Schmidt number was set to 0.9. The CFD model was integrated up to 3600 s with a time-step of 0.5 s.

Table 2. Average wind speed (ASOS 159) and PM_{2.5} concentration (AQMS 221112) for each wind direction. Wind speeds (2011–2020) and PM_{2.5} concentrations (2015–2020) are averages over school hours (07 LST to 18 LST).

Wind Direction	Wind Speeds (m s $^{-1}$)	$PM_{2.5}$ (µg m ⁻³)	Wind Direction Frequency (%)
northerly (N)	2.66	28.32	5.55
north-northeasterly (NNE)	2.79	22.02	4.41
northeasterly (NE)	2.69	18.45	12.05
east-northeasterly (ENE)	2.08	20.83	7.33
easterly (E)	2.14	23.95	6.73
east-southeasterly (ESE)	2.34	26.47	6.47
southeasterly (SE)	2.19	27.70	3.10
south-southeasterly (SSE)	1.89	28.77	1.50
southerly (S)	3.04	28.96	4.14
south-southwesterly (SSW)	3.87	33.05	11.55
southwesterly (SW)	4.65	28.55	8.30
west-southwesterly (WSW)	3.96	29.48	6.12
westerly (W)	3.52	27.57	6.23
west-northwesterly (WNW)	3.21	25.68	5.87
northwesterly (NW)	2.46	26.21	4.59
north-northwesterly (NNW)	2.69	28.16	6.04

2.3. Model Validation

For the T2M case close to the realistic configuration (most of the trees around the school were shrubs), we validated the CFD model against the wind directions and speeds measured by the 3D sonic anemometer and $PM_{2.5}$ concentrations measured by the sensor network around the school [25]. For the wind validation, we coupled the CFD model with the local data assimilation and prediction system (LDAPS), one of the numerical weather prediction systems operated by the Korea Meteorological Administration. The coupled model was integrated from 00 LST to 23 LST on 23 June 2020. The LDAPS provided the horizontal wind components (U and V) for the CFD model. We used the 1-h averaged $PM_{2.5}$ concentrations measured at the AQMS 221112 as the background concentrations. During the validation period, the emission rate of $PM_{2.5}$ was estimated using the method

described in Section 2.2 (Figure 2). The emission rate had two peaks, which were not distinct, at 07 and 17 LST. It was less than 10^{-6} kg m⁻² h⁻¹ in the early morning (01 LST and 04 LST) and had its maximum (3.64×10^{-6} kg m⁻² h⁻¹) at 17 LST.



Figure 2. Daily variation of the PM_{2.5} emission rate on the road in the target area.

For statistical validation, we used the root mean square error (RMSE), normalized root mean square error (NRMSE), geometric mean variance (VG), geometric mean bias (MG), fractional bias (FB), correlation coefficient (R), and fraction within a factor of two (FAC2) [26]:

$$RMSE = \sqrt{\left(C_{o} - C_{P}\right)^{2}}$$
(10)

NRMSE =
$$\sqrt{\frac{(C_o - C_P)^2}{C_o \cdot C_P}}$$
 (11)

$$VG = \exp\left[\overline{\left(\ln C_{o} - \ln C_{P}\right)^{2}}\right]$$
(12)

$$MG = \exp\left[\ln C_{o} - \ln C_{P}\right]$$
(13)

$$FB = \frac{(\overline{C_o} - \overline{C_P})}{0.5 (\overline{C_o} + \overline{C_P})}$$
(14)

$$R = \frac{\overline{(C_o - \overline{C_o})(C_P - \overline{C_P})}}{\sigma_{C_o} \cdot \sigma_{C_P}}$$
(15)

FAC2 = fraction of data that satisfy
$$0.5 \le \frac{C_P}{C_o} \le 2.0$$
, (16)

where C_0 , C_P , \overline{C} , and σ_C denote the measurements, model predictions, average across the dataset, and standard deviation across the dataset, respectively. The recommended criteria were NRMSE $< \sqrt{1.5}$, VG < 4, |MG - 1| > 0.3, |FB| < 0.3, R > 0.8, and FAC2 > 0.5.

Figure 3 shows the time series of the wind directions and wind speeds measured and simulated at the PKNU-SONIC station (the red dot in Figure 1a) located on the building roof (15 m above the ground). The measurement showed that the southwesterly wind persisted in the daytime and that northeasterly-to-northwesterly winds dominated at night (Figure 3a). LDAPS simulated the measured wind directions well, and the wind directions in the T2M case generally followed those of the LDAPS. The measured wind speeds were low (less than 2 m s⁻¹) and were stronger in the daytime than at night (Figure 3b). LDAPS overestimated the wind speed overall. The RMSEs for the wind directions and speeds of LDAPS were 56.63° and 3.20 m s⁻¹, respectively. The wind speeds of LDAPS did not satisfy the recommended criteria of the statistical indices, except for MG (0.27) (Table 3). The RMSEs for the wind directions and speeds in the T2M case were 63.60° and 0.73 m s⁻¹, respectively. The CFD model improved the prediction of wind speed and satisfied the NRMSE, VG, MG, FB, and FAC2 criteria.



Figure 3. Time series of the measured and simulated (**a**) wind directions and (**b**) wind speeds at PKNU-SONIC (red dot in Figure 1a).

Table 3. The statistical values of the wind speeds (m s⁻¹) simulated at PKNU-SONIC (red dot in Figure 1a).

	RMSE	NRMSE	VG	MG	FB	R	FAC2
LDAPS	3.20	1.65	5.86	0.31	$-1.10 \\ 0.15$	0.35	0.19
T2M	0.73	0.75	2.56	1.30		0.14	0.57

Figure 4 shows the time series of the PM2.5 concentrations measured and simulated at RF, R1, and R2 (green and yellow dots in Figure 1a). RF was located on the building roof (15 m above the ground), and R1 and R2 were located on lampposts adjacent to the roads (2 m above the ground). The measured $PM_{2.5}$ concentrations did not vary much during the measurement period (slightly high in the morning and almost constant otherwise) (Figure 4a). The maximum $PM_{2.5}$ concentration at RF was measured at 09 LST when the background concentration was maximal. Meanwhile, the maximum concentrations at R1 and R2, which were thought to be affected by road emissions, were measured at 10 LST. The CFD model underestimated the $PM_{2.5}$ concentrations in the early morning (00–08 LST) and late at night (21–23 LST) (Figure 4b–d). This underestimation was caused by the low emission rates at the corresponding times, as well as the low background concentrations, and contributed to relatively high RMSEs in the T2M case (RMSEs at RF, R1, and R2 were 4.25, 4.58, and 5.10 μ g m⁻³ per day, respectively). Nevertheless, the PM_{2.5} concentrations in the T2M case satisfied the NRMSE, VG, MG, FB, and FAC2 criteria. The CFD model simulated the PM_{2.5} concentrations better in the daytime than in the early morning and late at night (Table 4).



Figure 4. (a) Time series of the measurement, and measured and simulated PM_{2.5} concentrations at (b) RF, (c) R1, and (d) R2 (green and yellow dots in Figure 1a).

	Daytime			Early Morning and Late Night		
	RF	R1	R2	RF	R1	R2
RMSE	3.85	3.81	5.14	4.62	5.24	5.05
NRMSE	0.24	0.24	0.30	0.36	0.42	0.42
VG	1.07	1.05	1.09	1.18	1.23	1.24
MG	1.09	0.97	0.99	1.35	1.43	1.48
FB	0.06	-0.05	-0.05	0.26	0.33	0.35
R	0.44	0.37	0.41	-0.10	0.03	0.49
FAC2	1.00	1.00	1.00	0.92	0.92	0.92

Table 4. Statistical values of the PM_{2.5} (μ g m⁻³) concentrations simulated at RF, R1, and R2 (green and yellow dots in Figure 1a).

3. Results

3.1. Effects of the Wall-Type Fence

We analyzed the effects of the wall-type fence on airflow and $PM_{2.5}$ concentration from the perspective of aerodynamic mechanisms. The boxplots in Figure 5 summarizing the results for the 16 inflow directions in the W2M and W4M cases show the percentage changes in the $PM_{2.5}$ concentrations compared with the CNTL case in the school grounds and in the school boundary. The school boundary is the area within 4 m of the fences, and the school ground is the area excluding the school boundary. Regarding wall height, the magnitude of the $PM_{2.5}$ concentration change was more significant differences for the 4 m height than for the 2 m height. The $PM_{2.5}$ concentrations decreased significantly overall in the school boundary. In the school ground, the $PM_{2.5}$ concentrations decreased for most inflow directions, except for north–northwesterly to east–southeasterly directions. These results were explained through a detailed analysis of the flow and $PM_{2.5}$ concentration fields.



Figure 5. Box plots for the percentage changes of the $PM_{2.5}$ concentration (z = 1-11 m heights above the ground) for the W2M (**a**,**c**) and W4M (**b**,**d**) compared to the CNTL case in the school ground (left panels) and school boundary (right panels). The bars above and below the boxes indicate the upper and lower extremes, respectively. The upper, middle, and lower segments of the boxes indicate the upper quartiles, medians, and lower quartiles, respectively. The red and green lines indicate the mean value and the zero line, respectively.

We analyzed the flows and $PM_{2.5}$ concentrations for the east–southeasterly inflow in detail because the decrease in the $PM_{2.5}$ concentration was significant, and there were no obstacles between the road and the school ground, allowing effective analysis of the wall-type fence effects.

Figure 6 shows the wind vectors and the distributions of vertical wind components and $PM_{2.5}$ concentrations at the surface (z = 1 m) in the CNTL case. The flows along the roads around the school came into the school ground from the east school boundary, and complicated flows occurred within the school ground due to the influence of the surrounding buildings (Figure 6a). The flows coming in from the east school boundary formed a vortex near the northeast school building (①). In the school, the $PM_{2.5}$ concentration was lower than the background value because air pollutants transported from the background did not come to the surface due to the shielding effect of the topography and buildings. The $PM_{2.5}$ concentrations were high along the road and in high-density areas of buildings (Figure 6b). At the intersection of the north road (②) of the school, the $PM_{2.5}$ concentration was high because the pollutants were stagnant where the flow rotated. The relatively high $PM_{2.5}$ concentration on the road was transported into the school ground and the vortex region (①) from the east school boundary (Figures 6b and 7a).



Figure 6. (a) Wind vectors and shading of the vertical velocity distribution, (b) $PM_{2.5}$ concentrations at 1 m above the ground for the east–southeasterly inflow in the CNTL case.

In the W4M case, the wall-type fence on the east school boundary prevented the incoming flow into the school from the east road; therefore, a southerly wind occurred along the east road (Figure 8a). Downward flows appeared in the southeast school ground because of the flow coming over the fence, and the horizontal wind speeds weakened in the school ground. The blockage of pollutant transport by the wall-type fence increased the PM_{2.5} concentration on the road (Figure 8b). The PM_{2.5} concentrations decreased significantly in the downwind region of the wall-type fence because the fence restricted the emitted pollutants. However, the PM_{2.5} concentrations increased in the school ground as a result of pollutants coming over the wall-type fence (Figure 7b,c). The patterns of the flows and PM_{2.5} distributions in the W4M case were similar to those in the W2M case. However, in the W4M case, the vortex formed more significantly behind the wall-type fence than in the W2M case, with the result that the incoming pollutants into the downward region inside the fence were reduced further (Figure 7b,c). The wall-type fence effects restricting the PM_{2.5} concentrations transported from the road were similar for each inflow direction.

3.2. Effects of the Tree-Type Fence

We then analyzed the effects of the tree-type fence on the flow and $PM_{2.5}$ concentrations. The box plots (Figure 9) summarizing the results for the T2M and T4M cases for the 16 inflow directions show the percentage changes in the $PM_{2.5}$ concentrations compared to the CNTL in the school ground and school boundary. In the T2M and T4M cases, the horizontal wind speeds decreased largely because of the drag in the school ground, which had been planted with many trees (not shown). For each of the 16 inflow directions, the $PM_{2.5}$ concentration decreased in the school ground, where the wind speeds decreased.

The effects of tree-type fence on the $PM_{2.5}$ concentration in the school ground were similar to the effects in the school boundary. The magnitude of the $PM_{2.5}$ concentration change in the school boundary was similar in each inflow direction. However, the $PM_{2.5}$ concentrations decreased significantly in the school ground when easterly (from northeasterly to southeasterly) flows existed. This occurred because the drag effect was significant for the easterly inflow directions due to the absence of obstacles.



Figure 7. Streamlines and $PM_{2.5}$ concentrations in the vertical plane of y = 230 m for the east–southeasterly inflow direction in the (**a**) CNTL, (**b**) W2M, and (**c**) W4M cases.



Figure 8. For the east–southeasterly inflow, (**a**) wind vectors and shading of the vertical velocity distribution in the W4M case and (**b**) the difference in $PM_{2.5}$ concentrations of the W4M case compared to the CNTL case at 1 m above the ground.



Figure 9. The same as Figure 5, but for T2M (**a**,**c**) and T4M (**b**,**d**) in the school ground (left panels) and school boundary (right panels).

We analyzed the flows and PM_{2.5} concentrations for the east-northeasterly inflow, which showed a significant change in the $PM_{2.5}$ concentration. Figure 10 shows the wind vectors and the distributions of vertical wind components at the surface (z = 1 m)in the CNTL and T4M cases. In the CNTL case, the ambient wind was descended by the northwest school buildings (③), resulting in westerly flows around the northwest school ground (Figure 10a). Southerly flows were dominant in the south school ground. Upward flows appeared by convergence of opposite flows (westerly and southerly) in the school ground (④). In the T4M case, the 4-m-tall trees in the school ground greatly decreased the horizontal wind speeds up to a height of 5 m above the ground due to drag (Figure 11a,b), resulting in a shift of the flow convergence region to the southeast region ((5)) (Figure 10b). Additionally, the dominant westerly flows pushed the incoming flows from the east roads. Therefore, vertical velocities decreased at the vanished flow convergence region (④) and increased in the south school ground newly formed flow convergence region (⑤) (Figure 11d–f). The change in vertical velocity was relatively large above 5 m above the ground. The flow characteristics in the T4M case were similar to those in the T2M case, except for the magnitudes of the wind speed and the vertical velocity.

The PM_{2.5} concentrations were high along the north and east roads, where the flows converged, in the CNTL case (Figures 10a and 12a). The PM_{2.5} concentrations were relatively high near the south school ground, where downward flows were dominant, because of the high PM_{2.5} levels transported by the descending flows. The PM_{2.5} concentrations were relatively low in the upward flow regions (④). In the T4M case, the PM_{2.5} concentration in the north school ground increased as the upward flow weakened (Figures 10b and 12b). The PM_{2.5} concentration in the south school ground decreased in the upward flow region because the number of pollutants transported from the background to the surface decreased due to the upward flows. Moreover, the dominant westerly flow pushed emitted pollutants from the east roads, resulting in lower PM_{2.5} concentrations at the east boundary. The PM_{2.5} concentration changes caused by the vertical velocity were similar for each inflow direction.



Figure 10. Wind vectors and shading of the vertical velocity distribution at 1 m above the ground for the east–northeasterly inflow in (**a**) the CNTL case, and (**b**) the T4M case.



Figure 11. For the east–northeasterly inflow, the difference in the wind speed (upper panels) and vertical velocity (lower panels) of the T4M case compared to the CNTL case at 1 m (**a**,**d**), 5 m (**b**,**e**), and 9 m (**c**,**f**) above the ground.

3.3. Comparison of the PM_{2.5} Concentration by Wall- and Tree-Type Fences

We analyzed the $PM_{2.5}$ concentration vertically in the school by averaging the $PM_{2.5}$ concentrations simulated for 16 inflow directions using the inflow wind direction frequencies as the weighting (Table 2). Figure 13 shows the vertical profiles of the $PM_{2.5}$ concentration change rates for each case (W2M, W4M, T2M, and T4M) compared to the CNTL case averaged for the 16 inflow directions in the school ground and school boundary. In all cases, the $PM_{2.5}$ concentrations decreased compared to the CNTL case. The $PM_{2.5}$

concentration decreased with increasing height of walls and trees under both the wall- and tree-type fence cases. The change rates of the $PM_{2.5}$ concentration in the school ground were lower than the change rates in the school boundary. This occurred because the $PM_{2.5}$ concentration changes were offset where increasing and decreasing $PM_{2.5}$ concentrations existed simultaneously within the school ground. At the lower layer (below a height of 5 m above the ground), the tree effects (T2M and T4M) of reducing the $PM_{2.5}$ concentration were more significant than the wall-type fence effects (W2M and W4M) in the school ground (Figure 13a).



Figure 12. For the east–northeasterly inflow, (**a**) $PM_{2.5}$ concentration and (**b**) difference in $PM_{2.5}$ concentration between the T4M case and the CNTL case at 1 m above the ground.



Figure 13. Vertical profiles of the PM_{2.5} concentration change rates for each case compared to the CNTL case averaged for the 16 inflow directions in the (**a**) school ground and (**b**) school boundary.

This indicated that the prevention (by the tree-type fence) of pollutants incoming from the background due to increased vertical speed was greater than the prevention (by the wall-type fence) of pollutants emitted at the road. The PM_{2.5} change rates on the first and second floors of the school building in the T4M case were -1.10% and -0.68%, respectively (Table 5). However, with a higher wall-type fence height, the PM_{2.5} concentration was reduced even at the upper floors. The PM_{2.5} change rates on the third and fourth floors of the school building in the W4M case were -0.47% and -0.34%, respectively. In the T2M and T4M cases, the decrease rates in PM_{2.5} concentration in the school boundary were similar to the rates in the school ground (Figure 13b). However, the change rates in PM_{2.5}

concentration attributable to wall-type fence were significantly large because the wall-type fence prevented the transport of PM_{2.5} from the road. Specifically, the PM_{2.5} change rates on the first, second, third, and fourth floors of the school building in the W4M case were -9.47%, -3.30%, -1.44%, and -0.71%, respectively (Table 5). The standard deviations of the PM_{2.5} concentration calculated for 16 inflow directions also decreased with height as in the vertical variation of the change rate of the $PM_{2.5}$ concentration (Table 5). This indicates that the wall-type and tree-type fences were more effective at reducing the PM_{2.5} concentrations in a lower layer rather than a higher layer. However, at least in the lower layer, the reduction rate of the PM2.5 concentration was not proportional to the background $PM_{2.5}$ concentration. To evaluate the effects of the wall- and tree-type fences, we analyzed the PM_{2.5} concentrations averaged over the 16 inflow directions, using the frequencies of the measured wind directions as the weighting. Hence, the higher background $PM_{2.5}$ concentrations may not result in the higher PM_{2.5} concentrations around the school. Not only the background $PM_{2.5}$ concentration but also the wind speed and the frequency of an inflow should be taken into account to understand the effects of the fences around the school in this study.

Table 5. Change rate of $PM_{2.5}$ concentration by the school building floor for each case compared to the CNTL case (%). The parentheses indicate the standard deviations of the $PM_{2.5}$ concentration calculated for 16 inflow directions.

		First Floor	Second Floor	Third Floor	Fourth Floor
	W2M	-0.35(0.45)	-0.27 (0.38)	-0.22 (0.30)	-0.17 (0.25)
School	W4M	-0.79(0.29)	-0.58(0.25)	-0.47(0.24)	-0.34(0.17)
ground	T2M	-1.01(0.55)	-0.60(0.40)	-0.37(0.20)	-0.26 (0.15)
	T4M	-1.10(0.78)	-0.68 (0.62)	-0.43 (0.34)	-0.28(0.28)
	W2M	-3.11 (1.23)	-1.10 (0.47)	-0.54 (0.38)	-0.28 (0.28)
School	W4M	-8.47(2.97)	-3.30 (0.55)	-1.44(0.46)	-0.71 (0.25)
boundary	T2M	-1.45(0.56)	-0.83(0.42)	-0.54(0.28)	-0.35 (0.19)
	T4M	-1.78(0.77)	-0.95 (0.51)	-0.55 (0.40)	-0.36 (0.22)

4. Conclusions

We investigated the effects of wall- and tree-type fences on the airflows and PM_{2.5} concentrations in a school from an aerodynamics perspective using an RNG *k*- ε CFD model. The CNTL case assumed the absence of fences, and the wall and tree heights considered in the wall-type fence (W2M and W4M) and tree-type fence (T2M and T4M) cases were 2 m and 4 m.

To validate the simulated results against the measured wind speeds, wind directions, and $PM_{2.5}$ concentrations, the CFD model coupled with the LDAPS was integrated from 00 LST to 23 LST of 23 June 2020, for the T2M cases. The background $PM_{2.5}$ used was the measured $PM_{2.5}$ concentration at AQMS 221112. We calculated the $PM_{2.5}$ emission rate from the CAPSS based on the monthly, daily, and hourly emission factors. Although the CFD model underestimated the $PM_{2.5}$ concentrations from 00 LST to 08 LST, we concluded that the model simulated the wind speeds, wind directions, and $PM_{2.5}$ concentrations in the daytime well. The CFD model satisfied the recommended criteria (NRMSE, VG, MG, FB, and FAC2 criteria) for wind speeds and $PM_{2.5}$ concentration.

We evaluated the wall- and tree-type fence effects for 16 inflow directions by conducting numerical simulations with different fence types and heights. With the eastsoutheasterly inflow, in the CNTL case, relatively high $PM_{2.5}$ levels on the road were transported to the school from the east school boundary. The wall-type fence on the east school boundary prevented the incoming flow to the school from the east road, and the $PM_{2.5}$ concentrations decreased significantly in the downwind region of the fence because the fence restricted the emitted pollutants. However, the $PM_{2.5}$ concentrations increased in the school ground as a result of pollutants coming over the fences. With the east–northeasterly inflow, in the CNTL case, the ambient wind was descended by the northwest (south) school buildings, resulting in westerly (southerly) flows around the northwest (south) school ground. Upward flows appeared due to convergence of the opposite flows (westerly and southerly) in the school ground. The PM_{2.5} concentrations in the upward flow regions were relatively low. In the T4M case, the trees in the school ground greatly decreased the horizontal wind speeds due to drag, resulting in a shift of the flow convergence region to the southeast region. The $PM_{2.5}$ concentration in the north school ground increased as the upward flow weakened. The PM_{2.5} concentration in the south school ground decreased in the upward flow region because the number of transported pollutants from the background to the surface decreased due to the upward flows. As a result of analyzing the averaged PM_{25} concentrations for the 16 inflow directions, the PM_{2.5} concentrations in the school ground decreased in all cases (wall- and tree-type fences) compared to the CNTL case. At the lower layer, the tree-induced reductions of PM_{2.5} concentration in the school ground were more significant than those of the wall-type fences. This result indicated that the prevention by the tree-type fence of incoming pollutants from the background due to increased vertical speed was more significant than the prevention by the wall-type fence of pollutants emitted from the road. Note that the results suggested in this study had the following limitations. Thermal effects were not included in simulating the flow and pollutant dispersion. Tree trunks were not resolved in the model, and the leaf area index was uniform horizontally and vertically. The deposition of pollutants on the leaves was not considered. The emission rates on the road area were uniformly distributed.

Many studies have been conducted to improve the indoor and outdoor air quality in schools. The results of this study describe the effects of fences and trees and provide detailed and useful information regarding outdoor air quality in the school. Although the results of this study are limited to the target area, they provide meaningful information applicable to other schools surrounded by buildings. Additional studies on fences with various porosity values and trees with different leaf area densities are necessary to provide more realistic information about the outdoor air quality of schools.

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Nomenclature

Symbols

C_d	Drag coefficient
C_{μ}	Empirical constant
F _{ref}	Drag force term
i	Directional index
k	Turbulent kinetic energy
LAD	Fraction of the area covered by the vertical projection of leaves
n _c	Leaf area density
u _*	Frictional velocity

Wind speed
Horizontal wind component in the x-direction
Horizontal wind component in the y-direction
Vertical wind component
Roughness length
Boundary layer depth
Dissipation rate of turbulent kinetic energy
Air density
Wind direction
von Karman constant
Air quality monitoring system
Automatic weather station
Clean Air Policy Support System
Computational fluid dynamics
Fraction within a factor of two
Fractional bias
Geographic information system
Local data assimilation and prediction system
Geometric mean bias
Normalized root mean square error
Fine particulate matter
Correlation coefficient
Reynolds-averaged Navier-Stokes
Root mean square error
Renormalization group
Semi-implicit method for pressure-linked equation
Turbulence Kinetic Energy
Geometric mean variance

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