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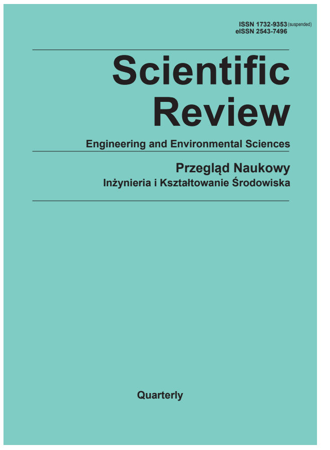

The role of roadside vegetation near school in mitigating air pollution: an exploratory case study in Zielonka

Michał TRZECIAK, Daria SIKORSKA

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Michał TRZECIAK[1]✉
Daria SIKORSKA[2]

[1]Warsaw University of Life Sciences – SGGW, Faculty of Civil and Environmental Engineering, Poland
[2]Warsaw University of Life Science – SGGW, Centre for Climate Research, Poland

✉m.trzeciak99@gmail.com

The role of roadside vegetation near school in mitigating air pollution: an exploratory case study in Zielonka

Keywords: urban air pollution, particulate matter, PM, urban vegetation, leaf area index, LAI, seasonal variation, children's exposure

INTRODUCTION

Air pollution is a major environmental and public health issue, with an estimated contribution to 7.9 million deaths in 2023. It currently ranks as the leading environmental risk factor for mortality worldwide, particularly impacting urban areas (Health Effects Institute & Institute for Health Metrics and Evaluation [HEI & IHME], 2025). Vehicle emissions and the use of fossil fuels for heating are significant sources of harmful pollutants (Karagulian et al., 2015; Liu et al., 2025). Children are particularly vulnerable to high pollutant concentrations due to their frequent outdoor activities, which can negatively impact their respiratory, cardiovascular, and cognitive health (Roche et al., 2024). Fine particulate matter (PM_1, $PM_{2.5}$, PM_{10}) poses significant health risks as it penetrates deep into the respiratory system (Kim et al., 2015). This exposure often occurs near roads and schools, highlighting the need for strategies to reduce pollution during children's daily commutes. One promising approach is the introduction and enhancement of urban greenery, which utilizes plants' ability to trap pollutants on the leaf surface. Urban vegetation, especially trees, can effectively capture airborne particles on leaf surfaces, thereby lowering concentrations of particulate matter (PM) and ultimately providing measurable health benefits (Escobedo et al., 2011; Nowak et al., 2014). These particles are primarily captured through interception, where they adhere to the leaf surface or become embedded in the wax layer (Przybysz et al., 2019). Research indicates that home-to-school walking routes with higher visible greenery are associated with better exposure metrics and increased potential for well-being benefits (Khanian et al., 2024). While most particles remain loosely attached and can be washed away by rain, those trapped in waxes are immobilized for extended periods (Beckett et al., 2000; Przybysz et al., 2014). Strategic planting of trees and shrubs can reduce ambient $PM_{2.5}$ levels by up to 10% in densely built environments (McDonald et al., 2007), resulting in significant health benefits that extend beyond improved respiratory health (Lee et al., 2015). However, seasonal, structural, and spatial factors limit the ability of urban trees to mitigate air pollution. Although vegetation can intercept airborne particles, its effectiveness depends on factors such as canopy density, species characteristics, and air circulation patterns (Barwise & Kumar, 2020). Seasonal variations further constrain performance; during winter dormancy, reduced leaf area leads to decreased pollutant interception. Trees along children's school routes provide limited PM reduction in winter, and dense vegetation can sometimes increase local pollutant concentrations (Hoppa et al., 2022).

In this study, we will evaluate how the density of roadside vegetation, measured by LAI, affects children's exposure to particulate matter (PM_1, $PM_{2.5}$, PM_{10}). We will collect data along the most frequented school routes in a suburban setting using a mobile PM monitoring device during typical morning commute hours. We aim to explore the relationship between LAI and PM levels based on two measurement campaigns representing leaf-off (March) and leaf-on (September) conditions. Our findings will provide valuable insight which may be useful to design vegetation interventions that effectively reduce children's exposure to pollutants.

MATERIAL AND METHODS

Study area

The study was conducted in the city of Zielonka, a suburban municipality on the eastern edge of the Warsaw metropolitan area, characterized by a mix of forested areas, low-density housing, small parks and several transport corridors. This heterogeneity creates neighborhood-scale contrasts in vegetation structure and traffic emissions relevant for analyzing particulate matter concentrations.
The town has four public primary schools, each situated in a distinct neighborhood (Fig. 1). We included all four schools to obtain geographically replicated sampling sites that capture variation in local vegetation and emission conditions within a single municipality. Primary schools provide an informative proxy for children's daily exposure because: (i) young children are more vulnerable to air pollution, (ii) Polish primary pupils typically attend the nearest school due to regionalization policies, meaning that the school environment reflects their immediate residential area, and (iii) this age group is the most likely to walk or use public transport, making the school surroundings representative of exposure conditions along their everyday commuting routes.

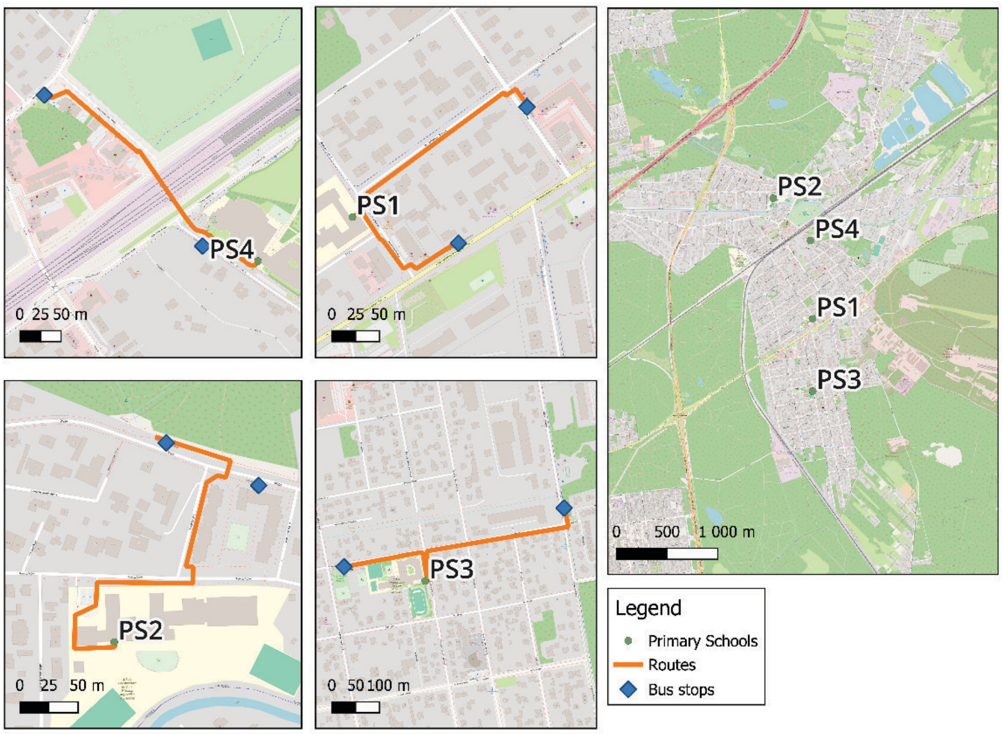

Figure 1. Study area within Zielonka, lines represent analyzed school routes
Source: own work on the basis of a background generated in portalmap OpenStreetMap (2025).

Traffic context

Detailed traffic count data were not available for all streets in Zielonka at the time of the study. However, the town is crossed by two major regional roads (No. 631 and No. 634), which can be classified as high-traffic routes based on the general traffic measurement conducted by the General Directorate for National Roads and Motorways (GDDKiA, 2020). These roads can be considered major sources of vehicular emissions in the study area. Primary School 1 (PS1) is located directly adjacent to one of these high-traffic roads, whereas Primary Schools 2 and 3 (PS2 and PS3) are situated approximately 500 m away. Primary School 4 (PS4) is located at a greater distance, approximately 1,000 m from the nearest major traffic corridor. Local residential streets along the school routes were assumed to carry substantially lower traffic volumes, typically on the order of 1,000–5,000 vehicles per day and were therefore expected to have a considerably smaller influence on ambient particulate matter dispersion compared to the main roads.

Sampling design and data collection

To identify the most relevant pedestrian routes for sampling, we combined pilot observations and local knowledge with GIS analysis (QGIS Development Team, 2023). Routes we chose were based on: (i) frequency of use by pupils commuting to school, (ii) presence of roadside vegetation with potential for air-quality mitigation, and (iii) accessibility from public transport stops and safe pedestrian pathways. For each school we mapped segments connecting the nearest bus stops to the school entrance (Fig. 1) and later verified them in the field. Segment lengths ranged from 230 m to 500 m, capturing areas where the majority of pupils are likely exposed to vegetation and traffic-related pollutants. Importantly, these routes were not treated as homogeneous units. They were selected to represent strong spatial gradients in vegetation structure, which are characteristic of school surroundings in Zielonka. Contrasts between sparsely vegetated street sections and highly vegetated areas near school grounds, parks, or forest edges allowed us to examine how particulate matter concentrations varied along short distances with changing canopy density.

Air pollution assessment

We measured PM_1, $PM_{2.5}$, PM_{10} concentrations along the selected routes using a Sniffer4D mobile air-quality monitor. The sensor was carried at a height of approximately 1.3 m to reflect the breathing zone of children. We conducted measurements on two weekday mornings, starting around 8:00 AM, corresponding to peak pupil commuting times and traffic intensity, ensuring representative exposure levels. We conducted field campaigns on March 19 (minimal vegetation cover) and September 4 (peak vegetation activity). Regional meteorological conditions were verified using archival data from the nearest available synoptic station (Institute of Meteorology and Water Management [IMGW-BIP], 2025). Both measurement days were dry, with no recorded precipitation. Mean daily wind speed was moderate in March (4.2 $m \cdot s^{-1}$) and low in September (about 2 $m \cdot s^{-1}$), indicating that strong wind-driven dispersion was unlikely to dominate particulate matter concentrations during the surveys.

Vegetation assessment

We quantified the potential of roadside vegetation to mitigate PM exposure using the LAI, which represents the total leaf area per unit of ground surface and serves as a key indicator of vegetation density and filtering capacity (Oguntunde et al., 2012). We measured LAI with the SunScan Canopy Analysis System at regular intervals along each route (approximately 30 m) to capture spatial variation in canopy cover. This allowed us to obtain detailed, segment-specific characterization of the vegetation children are exposed to during their commute.

Data analysis

We conducted statistical analysis in two steps. First, we calculated correlations between LAI and PM concentrations using Pearson's and Spearman's coefficients to capture both linear and monotonic relationships. The analysis was done in RStudio (R Core Team, 2025). To account for spatial heterogeneity, and potential modifiers of particulate matter concentrations, we used geospatial information from the BDOT10k topographic database (Head Office of Geodesy and Cartography [GUGiK], 2025). We assigned each PM measurement point a surrounding buffer (50 m radius) using GIS and quantified the proportion of built-up area. This variable reflects the surrounding urban structure, which can influence pollutant dispersion.
The number of spatial measurement points per school route ranged from 6 to 11. These points represent distinct locations with different vegetation and built-environment characteristics and were analyzed as spatial gradients rather than independent replicates.
Points are spatially autocorrelated and were treated as exploratory observations rather than independent replicates.
Our analysis focused on identifying potential associations between vegetation density along school commuting routes and children's exposure to particulate matter, while acknowledging that other factors – such as wind, urbanization, traffic patterns, and species composition, which also influence pollutant concentrations.

RESULTS AND DISCUSSION

We observed pronounced differences between leaf-off and leaf-on conditions, reflected in both vegetation structure and particulate matter concentrations (Table 1).

Table 1. Seasonal variation of leaf area index (LAI) and particulate matter (PM_1, $PM_{2.5}$, PM_{10}) concentrations with descriptive statistics

Parameter	Unit	Minimum	Maximum	Mean ±*SD*
Measurement	leaf-off			
LAI	–	0.1	2.5	0.57 ±0.43
PM_1	$\mu g \cdot m^{-3}$	25	48	32.5 ±3.75
$PM_{2.5}$	$\mu g \cdot m^{-3}$	36	81	50.59 ±6.96
PM_{10}	$\mu g \cdot m^{-3}$	38	89	54.66 ±8.44
Measurement	leaf-on			
LAI	–	0.6	8.7	5.47 ±2.21
PM_1	$\mu g \cdot m^{-3}$	4	25	7.26 ±1.74
$PM_{2.5}$	$\mu g \cdot m^{-3}$	6	44	9.35 ±3.14
PM_{10}	$\mu g \cdot m^{-3}$	6	45	9.92 ±3.19

Source: own work.

Particulate matter concentrations were substantially lower during leaf-on compared to leaf-off, reflecting both increased canopy density and the expected mitigation effect of urban vegetation. LAI was several times higher during leaf-on conditions, consistent with full canopy development. These seasonal contrasts shaped the magnitude and detectability of vegetation–PM relationships across the study area (Przybysz et al., 2019; Hoppa et al., 2022). Interestingly, while mean PM levels were consistently lower in leaf-on conditions, some maximum concentrations were actually higher than in leaf-off, indicating that dense vegetation can under certain conditions locally reduce airflow and enhance pollutant accumulation. This suggests that the effect of greenery is positive at low and moderate PM levels, but in episodes of extreme pollution, the vegetation can contribute to temporary local PM peaks.

Correlations between LAI and PM were weak but consistently negative (Table 2). This indicates a limited yet measurable influence of vegetation on reducing airborne particles. The strength of these relationships varied among the measurement points.

Table 2. Results of general Pearson's correlation analysis

Campaign	Size of	*r*	*p*	R^2
Leaf-off	PM_1	−0.16	*	0.02
	$PM_{2,5}$	−0.15	*	0.02
	PM_{10}	−0.16	*	0.02
Leaf-on	PM_1	−0.08	*	0.01
	$PM_{2,5}$	−0.09	*	0.01
	PM_{10}	−0.09	*	0.01

Source: own work.

Correlations between LAI and particulate matter were consistently negative but weak in both seasons (Table 2). *P*-values are included for completeness but should be interpreted with caution due to spatial autocorrelation and the limited independence of measurement points.

Small effect sizes suggest that vegetation explains only a minor share of PM variability at the scale of our transects, although local differences between schools indicate that spatial configuration of greenery and airflow patterns may also play an important role. The slightly stronger correlations observed in leaf-off conditions can be attributed to higher background pollution, which increases the detectability of vegetation-related effects. Even under leaf-off conditions, evergreen species and woody surfaces contribute to particle deposition, making vegetation signals more discernible during periods of elevated emissions (Hoppa et al., 2022).

Correlations calculated separately for each school (Table 3) revealed clear local differences. While all relationships were generally negative, their magnitude varied across sites and seasons, suggesting that vegetation effects are strongly conditioned by urban form, canopy structure, and nearby emission sources.

Table 3. Results of Pearson's correlation analysis for each school in leaf-off and leaf-on conditions

School	Leaf-off			Leaf-on			*n*
	size of	*r*	*p*	size of	*r*	*p*	
PS1	PM_1	−0.13	4.46×10^{-2}	PM_1	−0.19	*	7
PS1	$PM_{2,5}$	−0.12	**6.91×10^{-2}**	$PM_{2,5}$	−0.20	*	
PS1	PM_{10}	−0.01	**8.29×10^{-1}**	PM_{10}	−0.21	*	
PS2	PM_1	−0.28	*	PM_1	−0.38	*	10
PS2	$PM_{2,5}$	−0.25	*	$PM_{2,5}$	−0.48	*	
PS2	PM_{10}	−0.33	*	PM_{10}	−0.45	*	
PS3	PM_1	−0.35	*	PM_1	−0.01	**8.51×10^{-1}**	11
PS3	$PM_{2,5}$	−0.32	*	$PM_{2,5}$	0.02	**6.14×10^{-1}**	
PS3	PM_{10}	−0.31	*	PM_{10}	0.02	**5.60×10^{-1}**	
PS4	PM_1	−0.08	**1.97×10^{-1}**	PM_1	−0.15	6.21×10^{-3}	6
PS4	$PM_{2,5}$	0.08	**1.87×10^{-1}**	$PM_{2,5}$	−0.15	6.19×10^{-3}	
PS4	PM_{10}	0.06	**3.62×10^{-1}**	PM_{10}	−0.15	5.97×10^{-3}	

P-values are reported for completeness but should be interpreted with caution due to spatial autocorrelation and the lack of independent temporal replication. Please note that some values (marked in red) have $p \geq 0.05$.

Source: own work.

The highest correlations occurred for Primary Schools PS2 and PS3 in leaf-off conditions. In leaf-on conditions, correlations tended to strengthen, reflecting higher levels of vegetation. These findings highlight the context-dependent role of greenery, where vegetation effects on local air quality become more pronounced under higher pollution loads and in sheltered microenvironments.

Primary School 1 (PS1)

The PS1 route is dominated by low-density housing, wide streets, and sparse vegetation. PM concentrations were relatively uniform during leaf-off conditions, with minor increases near intersections, and decreased substantially during leaf-on conditions. Correlations between LAI and PM remained weak on both measurement days ($r \approx -0.13$ to -0.21). This may indicate that the limited and discontinuous canopy exerted only a small influence on local particulate levels.

Primary School 2 (PS2)

The PS2 route includes a forest edge, an open parking area, and a densely vegetated schoolyard. PM concentrations peaked over the parking zone in both measurement campaigns and declined sharply within the school grounds. This route showed some of the strongest correlations in the study ($r \approx -0.25$ to -0.48). This may suggest that where canopy cover is continuous and structurally diverse, vegetation is more closely associated with reductions in local particulate concentrations.

Primary School 3 (PS3)

The PS3 is situated within compact single-family housing with narrow streets and restricted airflow. In leaf-off conditions, PM concentrations were higher in areas with minimal greenery, yielding moderate negative correlations ($r \approx -0.31$ to -0.35). In leaf-on conditions, overall concentrations declined, likely because of low pollution levels and increased atmospheric mixing masked vegetation-related signals.

Primary School 4 (PS4)

The PS4 route follows a park boundary and passes through a railway underpass before continuing along low-density residential streets. PM concentrations were moderately high but spatially uniform in leaf-off conditions, likely due to effective ventilation provided by open park spaces. In leaf-on conditions, concentrations decreased and correlations remained weak ($r \approx -0.15$), indicating that vegetation effects were overshadowed by dispersion processes in this open setting.

Detailed comparison – individual school routes

Correlations between LAI and PM differed notably among the routes studied (Table 3), reflecting local variability in vegetation structure, built-up density, and microclimatic conditions observed on measurement days.

The PS1 route runs mainly through low-density residential areas with wide streets and sparse greenery. During leaf-off conditions, PM concentrations were relatively uniform, with slightly higher values near intersections (Fig. 2a). In leaf-on conditions, concentrations dropped considerably (Fig. 2b), mainly due to improved atmospheric dispersion and reduced emissions rather than vegetation effects. Correlations between LAI and PM were weak in both seasons ($r \approx -0.13$ to -0.21), indicating only a minor spatial association between canopy cover and particulate concentrations along this route.

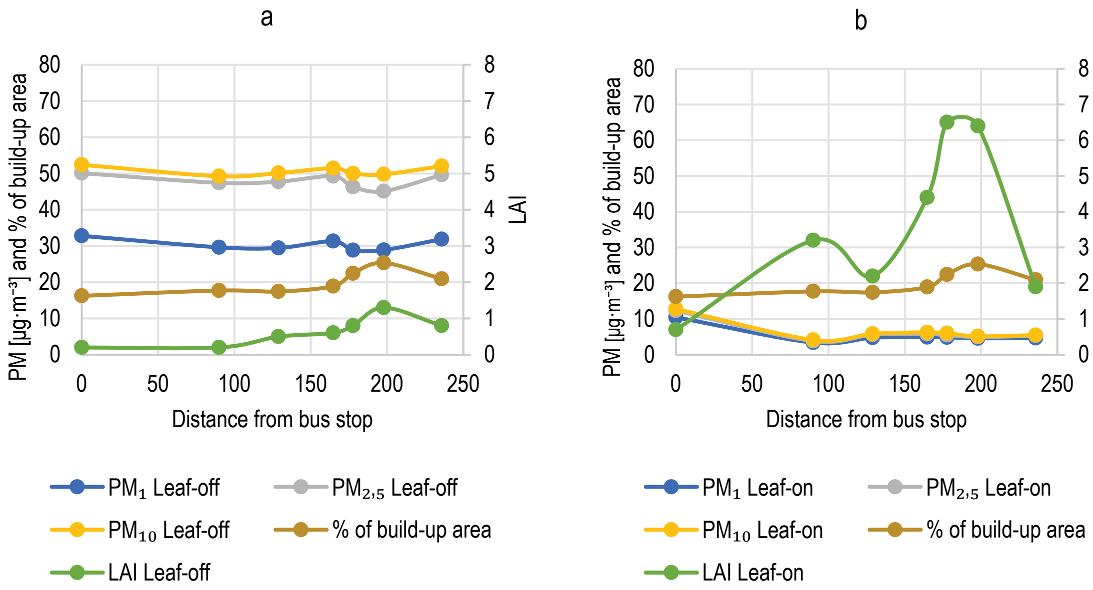

Figure 2. Leaf area index (LAI), percentage of build-up area and particulate matter (PM) concentrations across school route of Primary School 1 (detached housing, wide streets) in leaf-off (a) and leaf-on conditions (b)
Source: own work.

The PS2 route includes a mix of forest edge, open parking area, and vegetated schoolyard. In leaf-off conditions PM concentrations peaked over the parking zone and dropped sharply within the schoolyard (Fig. 3a). In leaf-on conditions, overall levels were lower but the spatial pattern remained similar (Fig. 3b). Here, correlations were one of the strongest among all schools ($r \approx -0.25$ to -0.48), suggesting that locations with denser and more continuous vegetation coincided with lower particulate matter concentrations, particularly where canopy continuity is high and air movement is unconstrained.

Primary School PS3 is located within a compact residential development characterized by narrow streets and limited air circulation. Leaf-off data (Fig. 4a) showed higher PM concentrations in zones with minimal greenery. The leaf-off relationship ($r \approx -0.31$ to -0.35) indicates a spatial co-occurrence of higher PM concentrations with areas of lower vegetation cover during a period of elevated background pollution. This is consistent with the role of evergreen vegetation in maintaining partial filtration capacity during periods of elevated emissions.

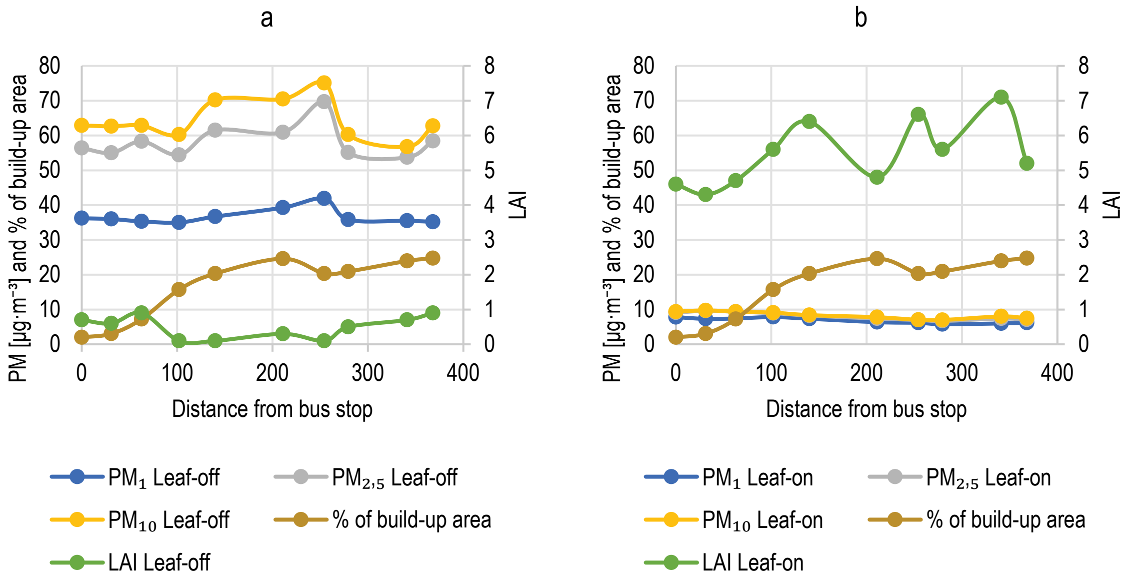

Figure 3. Leaf area index (LAI), percentage of build-up area and particulate matter (PM) concentrations across school route of Primary School 2 (mixed environment: forest, parking area, schoolyard) in leaf-off (a) and leaf-on conditions (b)
Source: own work.

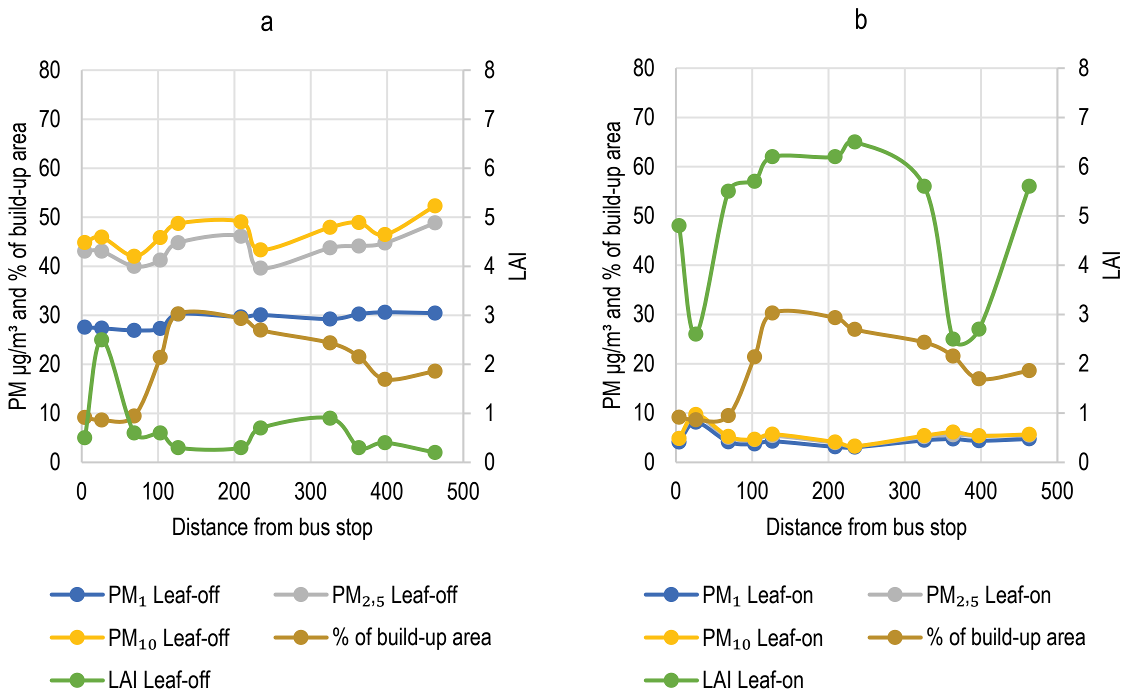

Figure 4. Leaf area index (LAI), percentage of build-up area and particulate matter (PM) concentrations across school route of Primary School 3 (narrow streets, compact single-family housing) in leaf-off (a) and leaf-on conditions (b)

The PS4 route follows a park boundary, passes through a railway underpass, and continues along the school fence near single-family homes. In leaf-off conditions, PM levels were moderately high but spatially uniform (Fig. 5a), likely due to efficient air mixing facilitated by open park spaces and tall trees. In leaf-on conditions (Fig. 5b), overall concentrations decreased, and correlations remained weak ($r \approx -0.15$), indicating that dispersion processes likely dominated over any direct vegetation-related spatial patterns.

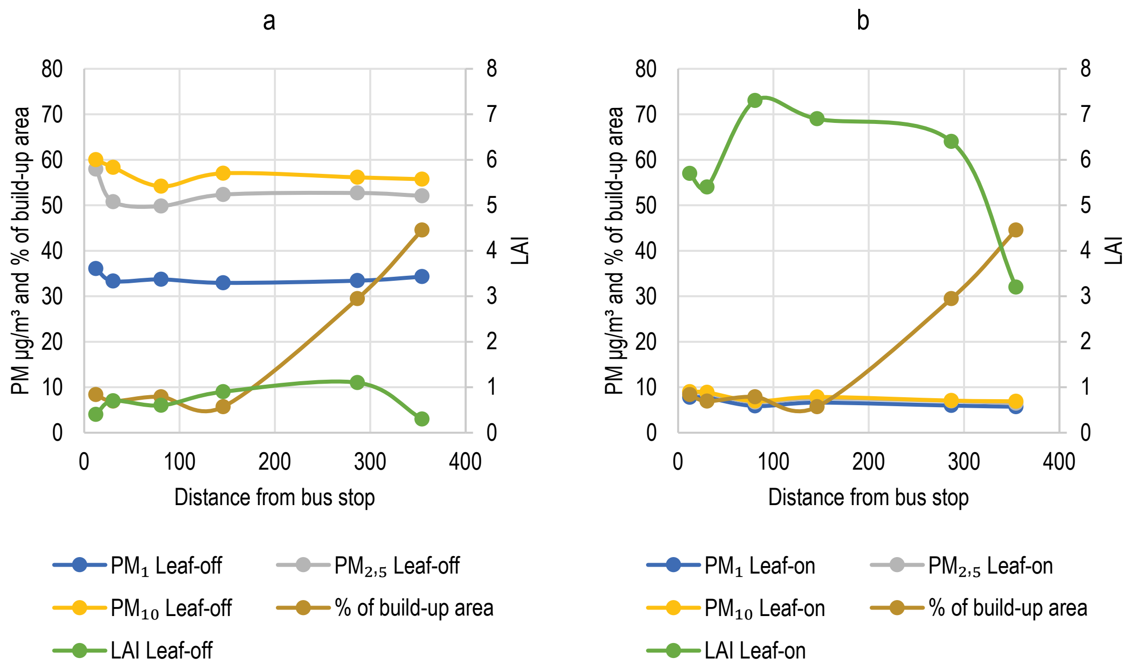

Figure 5. Leaf area index (LAI), percentage of build-up area and particulate matter (PM) concentrations across school route of Primary School 3 (route adjacent to park and railroad tracks) in leaf-off (a) and leaf-on conditions (b)
Source: own work.

Our results highlight three consistent patterns: (i) leaf-off conditions produced markedly higher PM concentrations, whereas leaf-on conditions produced higher LAI and lower pollution; (ii) vegetation–PM correlations were weak but consistently negative; and (iii) the strength of these relationships varied among school routes, reflecting differences in canopy continuity, street geometry, and local emissions.

These findings are broadly consistent with earlier work showing that urban vegetation can reduce airborne particle concentrations, but that such effects are typically localized and modest (Escobedo et al., 2011; Nowak et al., 2014; Janhäll, 2015). They also align with studies indicating that the influence of greenery becomes less detectable when emissions and meteorological conditions dominate the air-quality signal (Karagulian et al., 2015; Liu et al., 2025).

Seasonal patterns strongly shaped the relationship between vegetation and PM. During winter, PM concentrations were substantially higher due to residential heating and reduced atmospheric dispersion, which is consistent with previous work documenting the dominant role of emission intensity and stagnant conditions in shaping urban air quality (Juda-Rezler et al., 2020; Hoppa et al., 2022). These elevated background levels increased the contrast between more and less vegetated segments, making vegetation-related spatial associations more apparent in the data. Even with low LAI during leaf-off conditions, evergreen species and the deposition of particles on woody plant surfaces may still support modest filtration (Beckett et al., 2000; Przybysz et al., 2019).

In contrast, September measurements were characterized by much lower PM concentrations and higher atmospheric mixing. While LAI increased severalfold compared to March campaign, the low pollution background introduced greater variability relative to the vegetation signal, which likely masked small spatial differences linked to vegetation. This interpretation aligns with studies showing that foliage effectiveness depends on both canopy density and pollutant load (Przybysz et al., 2014; Barwise & Kumar, 2020).

Spatial heterogeneity: influence of urban form, canopy continuity, and local emissions

The strength of LAI –PM relationships varied clearly across the four school routes, reflecting differences in vegetation structure, street geometry, and local emission sources. The strongest correlations ($r \approx -0.25$ to -0.48) occurred at Primary School PS2, where the route includes a forest edge, dense tree cover on the school grounds, and a notable share of evergreen species. On measurement days this continuous and structurally diverse canopy likely enhanced filtration and created more stable airflow conditions, which supports findings that vegetation effects increase when the canopy forms a coherent barrier (Janhäll, 2015; Barwise & Kumar, 2020). These results highlight PS2 as a setting where vegetation structure aligns well with mechanisms known to promote particulate matter removal.

The Primary School PS3 also showed relatively strong associations in leaf-off conditions ($r \approx -0.31$ to -0.35), suggesting that evergreen vegetation and woody surfaces contributed to local particle deposition during periods of elevated emissions (Beckett et al., 2000; Przybysz et al., 2019). This route is located within a compact residential area, where narrow streets and closely spaced buildings limit air movement. In such settings, the dominant aerodynamic effect is often the formation of street-canyon turbulence, which tends to reduce the filtering role of trees by trapping pollutants and altering airflow patterns (Vos et al., 2013; Vranckx et al., 2015). This mechanism may explain why leaf-on correlations at Primary School PS3 were nearly absent: with full foliage, vegetation contributes to the canyon-like structure, increasing turbulence and masking any direct filtering effect. In March campaign, when deciduous foliage was minimal, the few evergreen patches stand out more clearly in the signal, likely contributing to stronger correlations. These results reinforce the context dependency of vegetation and PM relationships in compact residential street networks.

The Primary Schools PS1 and the PS4 had weaker relationships in both measurement campaigns ($r \approx -0.13$ to -0.21, and $r \approx -0.15$, respectively). Primary School PS1 is characterized by wide streets and dispersed tree cover, conditions that promote rapid dilution of pollutants and reduce the influence of individual planting elements. Primary School PS4 borders an open park with tall deciduous trees but few shrubs or evergreens, and the adjacent railway corridor further increases ventilation. These open settings are known to disperse pollutants efficiently, diminishing the relative effect of vegetation (Hoppa et al., 2022), as also observed in studies of children's routes where greenery shapes exposure only in specific micro-environments (Khanian et al., 2024). Overall, Primary Schools PS4 and the PS1 may illustrate conditions where open urban form and strong airflow override potential PM reduction by vegetation.

Implications for designing vegetation along children's school routes

Our findings show that the benefits of roadside vegetation are strongly context-dependent. The effectiveness of trees in reducing particulate matter depends on the continuity of the canopy, the presence of evergreen species, street geometry, and background emissions. Routes where vegetation forms a connected structure provide more stable filtration than those with isolated trees, and evergreen patches play an important role during winter, when deciduous foliage is absent. At the same time, urban form can either enhance or suppress vegetation effects. Narrow streets or semi-enclosed spaces may trap pollutants and limit ventilation, meaning that "more trees" do not automatically translate into better air quality (Vos et al., 2013; Janhäll, 2015).

These patterns highlight the need for case-by-case planning that considers not only vegetation configuration but also local airflow and street-canyon effects, rather than uniform greening strategies. Local green buffers near emission sources, short stretches of continuous canopy, and mixed plantings that include evergreens can improve exposure conditions. This is especially important in micro-environments where children spend the most time. Designing vegetation with attention to airflow, rather than relying solely on increasing tree density, appears essential in suburban settings like ours.

Beyond air-quality benefits, greenery along school routes provides additional psychological and behavioral advantages, supporting children's wellbeing, comfort, and walking experience (Lee et al., 2015; Khanian et al., 2024). These broader gains reinforce the value of integrating vegetation strategically into the everyday mobility of young pupils.

Even small reductions in particulate matter can be meaningful for children's health, given their heightened vulnerability and the long-term consequences of early-life exposure (Kim et al., 2015; Roche et al., 2024). Our results contribute to the broader discussion on designing resilient urban environments that support safe and healthy school mobility. By showing where vegetation can offer benefits, and where its effect is constrained by urban form, we provide evidence that can inform planning decisions, from shaping pedestrian routes to prioritizing targeted greening. Strengthening green infrastructure along everyday walking paths has the potential to enhance both environmental conditions and children's wellbeing. In this sense, even modest effects of vegetation play an important role in creating healthier school surroundings.

Future studies could build on our findings by incorporating multi-season or multi-year measurements to capture a wider range of meteorological and vegetation conditions. Combining empirical transects with dispersion modeling would allow a more precise assessment of how street geometry and airflow shape children's exposure (Vranckx et al., 2015). Detailed species-level and structural analyses would help clarify which vegetation forms contribute most effectively to particulate removal. Integrating LAI with real-time traffic counts and emission inventories could further disentangle the relative influence of greenery and anthropogenic sources. These extensions align with calls to better integrate vegetation metrics with urban form when evaluating air-quality interventions (Barwise & Kumar, 2020).

Limitations of the study

Our study has several limitations. We conducted only two measurement campaigns, effectively representing single-day snapshots for leaf-off and leaf-on conditions which means that short-term meteorological variability could not be fully controlled. Because measurements were collected along continuous routes at short spatial intervals, individual observation points are spatially autocorrelated and do not represent independent replicates.

LAI was measured along transects capturing horizontal leaf cover rather than a continuous vertical canopy profile, which may have limited our ability to assess the role of tree structure as a barrier for particulate matter. The Sniffer4D, like other optical particle counters, is affected by humidity and particle composition, which can introduce bias in absolute concentration values. We also lacked detailed information on traffic flow along the surveyed routes, even though vehicle emissions are a major driver of PM variability in suburban areas (Karagulian et al., 2015; Liu et al., 2025). While we selected measurement days with low to moderate wind to minimize dispersion effects, we did not explicitly measure local airflow, which may influence pollutant concentrations at micro-scales. Finally, our analysis relied on correlations, based on spatially structured data, without repeated measurements on multiple days, which cannot establish causality and can underestimate the influence of general factors affecting PM variability when the underlying signal is small or masked by meteorological noise. These constraints underline the need for cautious interpretation of the strength and direction of the observed relationships.

CONCLUSIONS

We found that roadside vegetation was modestly associated with lower PM concentrations along school routes in Zielonka, generally coinciding with several-fold reductions in PM. However, in some locations, vegetation coincided with local peaks, causing occasional increases in maximum PM values. Overall, the correlation between green cover and PM remained weak. Dense built-up areas showed little effect. PM levels were higher during leaf-off conditions, when vegetation impact was more detectable, while in leaf-on conditions, background PM was lower and vegetation effects harder to isolate.
Our results highlight that vegetation's air-quality benefits are context-dependent. Canopy continuity, local geometry and pollution background determine whether greenery acts as a net sink or, occasionally, as a factor that alters local dispersion.
We therefore caution against simple prescriptions such as "more trees always improve air quality."
We recommend further studies with multi-season or multi-year monitoring, concurrent meteorological measurements, and dispersion modeling. Species-level and structural analyses of vegetation should be included. Such work would better inform targeted greening strategies to reduce children's exposure near schools.

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Summary

The role of roadside vegetation near school in mitigating air pollution: an exploratory case study in Zielonka. This study investigates the role of urban vegetation in mitigating particulate matter (PM_1, $PM_{2.5}$, PM_{10}) pollution along school routes in Zielonka, a small town near Warsaw. Measurements were collected during leaf-off (March) and leaf-on (September) conditions using a Sniffer4D mobile air quality monitor carried along pupils' commuting paths, alongside vegetation density estimates obtained with a SunScan Canopy Analysis System. Initial correlation analyses across the entire dataset revealed weak negative relationships between leaf area index (LAI) and particulate concentrations. To refine interpretation, the study introduced spatial stratification using built-up area percentages derived from the BDOT10k topographic database. While mean PM levels decreased with higher LAI, occasional local maxima were observed in dense canopy sections. The findings highlight that vegetation's effectiveness in improving air quality is highly context-dependent, shaped by urban form and season. Although the explanatory power was modest, the results emphasize the importance of integrating vegetation and built-environment interactions in air quality assessments. Further studies with broader spatial and temporal coverage are recommended to better characterize these relationships and guide targeted greening strategies along school routes.