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Comparative Effectiveness of Three Roadside Tree Species in Reducing PM2.5–PM10 Along Jagorawi Toll Road

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ABSTRACT

Vehicular activity along urban toll road corridors contributes to particulate matter emissions that degrade air quality and increase public health risks, particularly respiratory and cardiovascular disorders. Roadside greenbelts are considered a nature-based solution for reducing airborne particles; however, comparative evaluations of roadside tree species for PM2.5 and PM10 mitigation remain limited. This study evaluated the reduction performance of three commonly planted roadside tree species, namely *Lagerstroemia speciosa, Gmelina arborea,* and *Mimusops elengi,* along the Jagorawi Toll Road. Particulate concentrations were measured in three vegetated plots and one non-vegetated control plot on 26, 28, and 30 April 2025 using calibrated *Dienmern DM72B* digital air quality detectors. Measurements were conducted simultaneously at 0, 10, and 30 m sampling points, with the 0 m point located at the first roadside tree row, approximately 5 m from the road edge. Leaf Area Index (LAI), leaf particulate retention capacity, microclimate, and traffic volume were also recorded. Vegetated plots reduced PM2.5 and PM10 concentrations by 30.82% and 29.23% on average, respectively, compared with the control at the same sampling distances. The plot dominated by *M. elengi* showed the largest average reduction, supported by the highest LAI value (2.1639) and leaf retention capacity (0.20 mg/cm²). These findings indicate that dense, high-LAI roadside tree canopies can improve PM2.5 and PM10 mitigation. However, species effects should be interpreted together with planting structure and site conditions. This study supports prioritizing high-LAI and dense-canopy species in roadside greenbelt planning.

Keywords: Jagorawi toll road, particulate matter, PM2.5, PM10, roadside greenbelts

INTRODUCTION

Air pollution is one of the major environmental challenges in urban areas and is closely associated with the increasing intensity of transportation activities. Particulate matter (PM), particularly PM2.5 and PM10, is of concern because these particles can remain suspended in the air and enter the human respiratory system. Exposure to particulate matter has been associated with respiratory and cardiovascular health risks, including acute respiratory infections and premature mortality (Kiihamäki *et al.* 2024). Therefore, reducing particulate pollution in areas with high vehicular activity is an important aspect of urban environmental management.

In rapidly urbanizing regions such as Jakarta, vehicular emissions are an important source of particulate pollution. Road transport emissions include exhaust pollutants and non-exhaust sources such as tire wear, brake abrasion, and road surface resuspension, which may contribute substantially to traffic-related PM2.5 (Saarikoski *et al.* 2024). High-traffic corridors, including toll roads, may therefore function as particulate pollution hotspots because they receive continuous vehicle flow and generate particulate emissions over extended periods.

Nature-based Solutions (NbS), particularly roadside greenbelts, have been recognized as a practical approach to mitigating air pollution along transportation corridors. Vegetation can reduce airborne particulates through deposition on leaf surfaces and modification of airflow patterns. The effectiveness of roadside vegetation is influenced by canopy density, planting structure, leaf morphology, and Leaf Area Index (LAI) (Janhäll 2015; Abhijith *et al.* 2017). These characteristics indicate that the role of greenbelts in reducing particulate pollution is not only determined by the presence of vegetation, but also by the structural and morphological characteristics of the tree species used.

Several studies in Indonesia have demonstrated the role of roadside vegetation in reducing pollutant concentrations. Vegetated roadside areas have been reported to show lower pollutant levels than non-vegetated areas (Dwirahmawati *et al.* 2018), and vegetation structure has been shown to influence pollutant dispersion near road corridors (Desyana *et al.* 2017). Previous studies have also examined roadside vegetation in relation to gaseous pollutants such as

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NO_2 and CO (Nasrullah *et al.* 2001; Izzah *et al.* 2019), while recent research on toll road greenbelts has shown the potential of vegetation in reducing PM10 concentrations compared with open areas (Syahraeni *et al.* 2024). However, most Indonesian roadside vegetation studies have focused on gaseous pollutants or on general comparisons between vegetated and non-vegetated plots. Comparative evaluations of commonly planted roadside tree species in reducing PM2.5 and PM10 remain limited.

This study was developed to address this gap by evaluating the comparative effectiveness of three commonly planted roadside tree species, namely *Lagerstroemia speciosa*, *Gmelina arborea*, and *Mimusops elengi*, in reducing PM2.5 and PM10 concentrations along the Jagorawi Toll Road. The study compared three vegetated plots dominated by these species with one non-vegetated control plot. PM2.5 and PM10 concentrations were measured at 0, 10, and 30 m sampling points, while LAI, leaf particulate retention capacity, microclimatic variables, and traffic volume were also observed to explain factors associated with particulate reduction.

This study hypothesized that vegetated plots would show lower PM2.5 and PM10 concentrations than the non-vegetated control plot, and that plots with higher LAI, denser canopy structure, and greater leaf particulate retention capacity would show greater particulate reduction. The results are expected to support roadside greenbelt planning by providing information on tree species and vegetation characteristics that contribute to PM2.5 and PM10 mitigation along toll road corridors.

METHODS

Study Area and Sampling Period

The study was conducted along the roadside greenbelt of the Jagorawi Toll Road, DKI Jakarta Province, on the section heading toward Bogor between Dukuh 2 Toll Gate and Cibubur 3 Toll Gate, extending from north to south. Four sampling plots were established at km 10+400, km 11+400, km 12+200, and km 12+800. The first three plots were vegetated plots dominated by *Lagerstroemia speciosa* (Plot 1), *Gmelina arborea* (Plot 2), and *Mimusops elengi* (Plot 3), while Plot 4 was a non-vegetated control plot. The locations and sampling schedule are presented in Figure 1 and Table 1. These three species were selected because they are commonly used as roadside trees, are dominant in the observed Jagorawi Toll Road greenbelt corridor, and represent different canopy characteristics.

PM2.5, PM10, and microclimate measurements were conducted on 26, 28, and 30 April 2025. Measurements were carried out during three observation periods: 08:00–09:00, 12:00–13:00, and 16:00–17:00 WIB. All plots were measured simultaneously during each observation period by

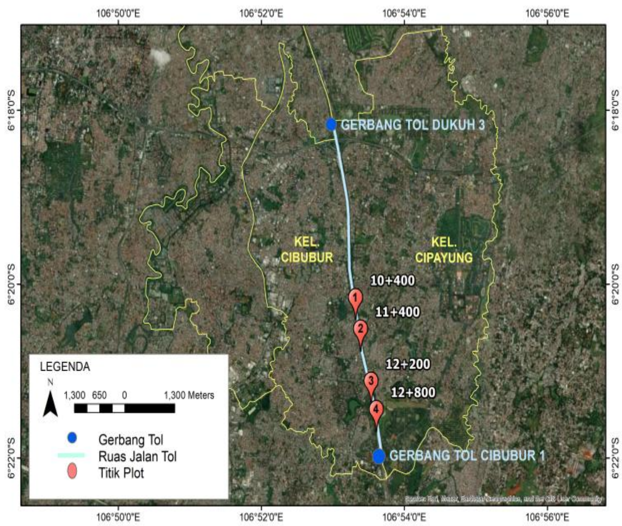


Figure 1 Study area and sampling plots along the Jagorawi Toll Road, DKI Jakarta.

Table 1 Location and sampling schedule of the study plots

Plot	Location (km)	Vegetation	Sampling time (WIB)
1	10+400	Bungur (*Lagerstroemia speciosa* (L.) Pers.)	08:00–09:00; 12:00–13:00; and 16:00–17:00 (same for all plots)
2	11+400	Gmelina (*Gmelina arborea* Roxb.)	
3	12+200	Tanjung (*Mimusops elengi* L.)	
4	12+800	Non-vegetated control plot	

different field teams to minimize temporal variation in particulate concentration caused by short-term changes in traffic and atmospheric conditions. Leaf samples for particulate retention analysis were collected on 22 April, 30 April, and 7 May 2025, while Leaf Area Index (LAI) measurement was conducted on 7 May 2025.

The main instruments used in this study included a digital air quality detector, a Low Volume Air Sampler (LVAS) for calibration, microclimate measuring instruments, and a laptop for data processing.

Instruments and Data Collection

1. Instrument Calibration

The instruments, materials, and data sources used in this study are summarized in Table 2. PM2.5 and PM10 concentrations were measured using Dienmern DM72B digital air quality detectors. The measurement range of the instrument was 0–999 μg/m³, with a resolution of 1 μg/m³ for both PM2.5 and PM10. Prior to field measurement, the digital air quality detectors were calibrated using a Low Volume Air Sampler (LVAS) on 12 March 2025 at Jalan Raya Dramaga. The calibration was conducted for PM2.5 and PM10, and the correction factor obtained from the calibration process was applied to the particulate concentration data. Filter samples obtained from the LVAS were analyzed at PT Almost Laboratorium Indonesia to ensure measurement accuracy and comparability of results.

2. Particulate Measurement

Particulate measurements were conducted at three sampling points in each plot, namely 0, 10, and 30 m. The 0 m point did not refer to the road edge, but to the nearest sampling point located at the first roadside tree row, approximately 5 m from the road edge. The 10 m and 30 m points were measured inward from this 0 m point. The same distance arrangement was also applied to the non-vegetated control plot. The sampling points at each vegetated plot and the control plot are illustrated in Figure 2. During measurement, the air quality detector was positioned approximately 1.5 m above ground level. Particulate concentrations were recorded at 10-minute intervals for one hour during each observation period.

3. Microclimate Measurement

Microclimate variables, including air temperature, relative humidity, wind speed, and wind direction, were measured at each plot during the same observation periods as the PM2.5 and PM10 measurements. Traffic volume data were obtained from PT Jasa Marga (Persero) Tbk for the corresponding sampling dates and observation periods.

4. Leaf Area Index (LAI) Measurement

Leaf Area Index (LAI) was measured using hemispherical canopy photography and analyzed with HemiView 2.1 Canopy Analyzer. Photographs were taken below the tree canopy using a fisheye camera positioned vertically upward. LAI measurements were conducted with three replications for each vegetated plot. In each replication, photographs were taken at two points within the roadside greenbelt, namely at the 0 m and 10 m points. The control plot was not measured for LAI because it did not contain roadside tree vegetation. The resulting hemispherical images were processed in HemiView 2.1 to obtain LAI values for each dominant tree species.

5. Leaf Particulate Retention Measurement

Leaf particulate retention capacity was measured using a gravimetric method. Leaf samples were collected from the dominant tree species in each vegetated plot. The selected leaves were fully expanded, green, healthy, and taken from the second or third position from the tip and base of the branch.

Table 2 Types of data, instruments, and data sources

Activity	Instruments and materials	Purpose	Data source
Instrument calibration of digital air quality detector	Low Volume Air Sampler (LVAS), filter paper, digital air quality detector	To calibrate the digital instrument to improve measurement accuracy for PM 2.5 and PM 10	Field observation
PM2.5 and PM10 concentration measurement	Dienmern DM72B digital air quality detector	To measure PM2.5 and PM10 concentrations	Field observation
Traffic volume recording	—	To analyze the relationship between traffic volume and particulate concentration	PT Jasa Marga (Persero) Tbk
Leaf Area Index (LAI) measurement	Camera, fisheye lens	To obtain LAI values	Field observation
Microclimate measurement (temperature, humidity, wind speed, wind direction)	Digital anemometer, digital thermometer, compass, windsock	To determine microclimatic conditions during particulate measurement	Field observation
Data analysis	Microsoft Excel, HemiView 2.1, and IBM SPSS Statistics 26	To perform LAI analysis, comparative tests, regression, and correlation analysis	Primary and secondary data
Leaf particulate retention capacity analysis	Distilled water, beaker glass, analytical balance, portable leaf area meter, laboratory oven	To determine the effectiveness of each tree species in trapping particulate particles	Primary data

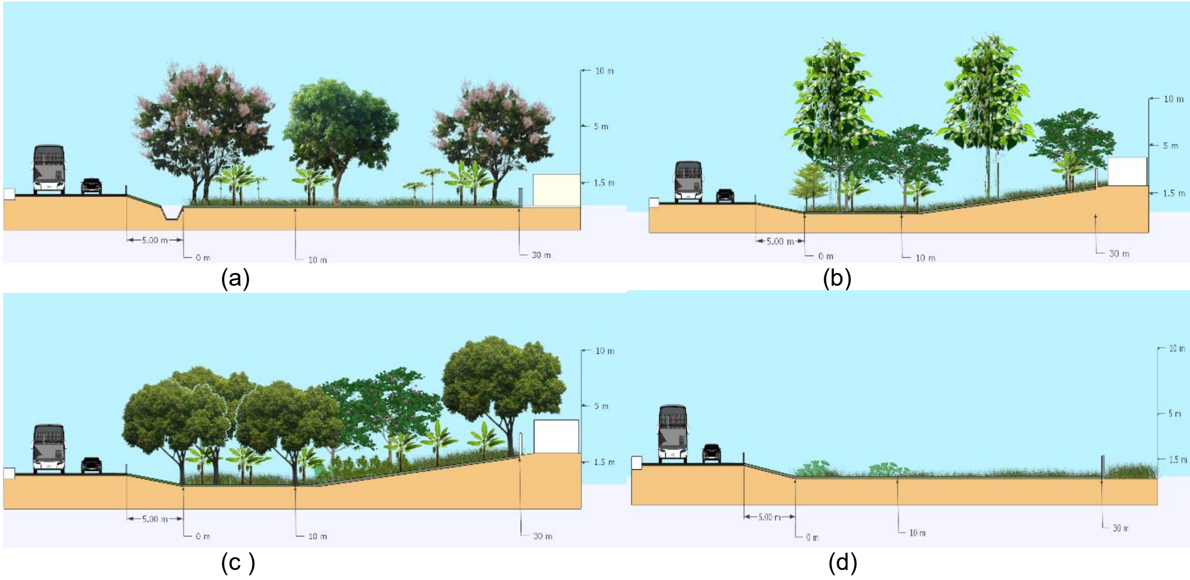


Figure 2 Illustration of air sampling points at (a) *Lagerstroemia speciosa*, (b) *Gmelina arborea*, (c) *Mimusops elengi*, and (d) non-vegetated control plot.

Approximately 20 g of leaves were collected for each replication, with three replications for each species.

Each leaf sample was washed using 100 mL of distilled water to remove particles deposited on the leaf surface. The washing solution was collected in a pre-weighed beaker and oven-dried for 24 hours until the water evaporated, leaving dry particulate residue. The retained particulate mass was calculated as the difference between the final weight of the beaker containing dry residue and the initial weight of the empty beaker. Leaf area was measured using a portable leaf area meter. Leaf particulate retention capacity was calculated using the following equation:

$$\text{Leaf particulate retention capacity (mg/cm}^2\text{)} = \text{retained particulate mass (mg) / leaf area (cm}^2\text{)}.$$

The percentage of leaf particulate retention effectiveness was calculated separately from PM2.5 and PM10 concentration reduction. Therefore, leaf retention effectiveness represents the ability of leaf samples to retain particulate residue, whereas PM2.5 and PM10 reduction represent the decrease in airborne particulate concentration in vegetated plots compared with the non-vegetated control plot.

Data Analysis

PM2.5 and PM10 reduction percentages were calculated by comparing the mean particulate concentration of each vegetated plot with the non-vegetated control plot at the same sampling distance using the following equation:

$$\text{PM reduction (\%)} = [(\text{Ccontrol} - \text{Cvegetated}) / \text{Ccontrol}] \times 100$$

Where Ccontrol is the particulate concentration in the non-vegetated control plot, and Cvegetated is the particulate concentration in the vegetated plot at the same sampling distance. The percentage reduction of PM2.5 and PM10 concentrations in the vegetated plots compared with the control plot.

Statistical analyses were performed using Microsoft Excel and IBM SPSS Statistics 26. Normality tests were conducted prior to comparative analysis. One-way analysis of variance (ANOVA) was used to evaluate differences in PM2.5 and PM10 concentrations among plots at a 5% significance level. When ANOVA results were significant, Bonferroni post hoc tests were used to identify differences among plots.

Simple linear regression analysis was applied to examine the relationship between particulate concentrations and environmental variables, including sampling distance, traffic volume, air temperature, relative humidity, and wind speed. Regression analysis was also used to evaluate the relationship between particulate concentrations and vegetation-related variables, including leaf particulate retention capacity and LAI.

RESULTS AND DISCUSSION

General Characteristics of the Study Area

The study area consisted of three vegetated plots and one non-vegetated control plot located along the Jagorawi Toll Road corridor in East Jakarta. Plot 1 was dominated by *Lagerstroemia speciosa* and located at km 10+400 in Cipayung Subdistrict. This plot was characterized by relatively flat topography and a single primary row of roadside trees. Plot 2 was dominated by *Gmelina arborea* and located at km 11+400, also in

Cipayung Subdistrict. This plot had slightly elevated topography and a multi-row planting structure with relatively higher tree density. Plot 3 was dominated by *Mimusops elengi* and located at km 12+200 in Cibubur Subdistrict, Ciracas District. This plot was characterized by sloping topography and compact, continuous canopy coverage along the roadside. Plot 4, the non-vegetated control plot, was located at km 12+800 in Cibubur and had relatively flat topography without significant roadside tree cover.

The differences in plot characteristics indicate that particulate reduction in this study was not influenced by tree species alone, but also by planting structure, canopy continuity, topography, and site conditions. Therefore, the results are interpreted as differences among roadside greenbelt plots dominated by different tree species, rather than as a purely species-level comparison.

Microclimate Conditions

Microclimate observations during the sampling periods are presented in Table 3. Air temperature ranged from 30.7 to 36.4°C, while relative humidity ranged from 38.0 to 71.1%. Wind speed varied from 0.2 to 2.3 m/s, with the dominant wind direction generally originating from the south. These conditions indicate relatively warm conditions with low to moderate wind speed during the observation period. Low wind speed may limit horizontal dispersion and allow particulate matter to remain near the roadside environment for longer periods. However, because the effect of microclimate variables was evaluated only through

Table 3 Microclimate conditions during sampling periods

Plot	Date	Observation time	Air temperature (°C)	Relative humidity (%)	Wind speed (m/s)	Dominant wind direction
Plot 1 (*L. speciosa*)	26/04/2025	08:00–09:00	33.0	62.6	0.8	South
		12:00–13:00	34.2	59.1	0.7	South
		16:00–17:00	33.1	65.3	0.7	South
	28/04/2025	08:00–09:00	33.9	53.5	0.6	Southwest
		12:00–13:00	35.6	45.4	1.3	Southeast
		16:00–17:00	33.8	52.3	1.1	Southeast
	30/04/2025	08:00–09:00	31.5	57.8	0.4	West
		12:00–13:00	35.0	39.4	0.8	East
		16:00–17:00	33.8	48.1	1.1	West
Plot 2 (*G. arborea*)	26/04/2025	08:00–09:00	32.4	65.6	0.4	South
		12:00–13:00	33.5	57.4	0.4	South
		16:00–17:00	31.6	69.1	0.3	South
	28/04/2025	08:00–09:00	34.2	64.6	0.4	South
		12:00–13:00	36.4	54.2	0.8	South
		16:00–17:00	36.0	58.1	1.0	South
	30/04/2025	08:00–09:00	30.7	63.1	0.8	South
		12:00–13:00	33.4	49.3	0.5	South
		16:00–17:00	32.5	55.1	1.0	South
Plot 3 (*M. elengi*)	26/04/2025	08:00–09:00	33.6	62.5	0.2	South
		12:00–13:00	34.3	57.3	0.2	South
		16:00–17:00	32.2	66.2	0.3	Southeast
	28/04/2025	08:00–09:00	31.8	64.8	0.6	South
		12:00–13:00	33.1	62.1	0.6	South
		16:00–17:00	31.7	66.8	0.7	South
	30/04/2025	08:00–09:00	31.7	68.4	0.7	South
		12:00–13:00	34.5	58.2	0.6	South
		16:00–17:00	33.4	71.1	0.4	South
Plot 4 (Control)	26/04/2025	08:00–09:00	34.2	52.0	1.3	South
		12:00–13:00	35.4	45.4	1.2	South
		16:00–17:00	32.7	56.4	1.2	South
	28/04/2025	08:00–09:00	33.9	40.8	0.9	South
		12:00–13:00	35.3	38.0	1.3	South
		16:00–17:00	33.6	46.0	2.3	South
	30/04/2025	08:00–09:00	33.5	50.2	1.3	South
		12:00–13:00	34.4	44.7	0.6	South
		16:00–17:00	32.1	57.1	1.4	South

simple regression, these conditions are interpreted as supporting environmental information rather than as dominant explanatory factors.

Traffic Volume

Traffic volume during the sampling periods is shown in Table 4. The combined traffic volume from Cibubur 1 Toll Gate and GMU Cibubur Toll Gate ranged from 2,292 to 2,957 vehicles per hour. The highest traffic volume was recorded on 28 April 2025 during the 12:00–13:00 observation period. Because PM2.5 and PM10 measurements were conducted simultaneously with traffic and microclimate observations, these data provide supporting information for interpreting particulate concentration patterns across plots. Although the GMU Cibubur entrance volume decreased to 893 vehicles during the 16:00–17:00 period on 28 April 2025, the combined traffic volume remained within the observed range and was therefore used as recorded in the analysis.

Regression analysis showed that traffic volume had higher R^2 values than most microclimate variables in relation to PM2.5 and PM10 concentrations. This indicates that traffic volume was more consistently associated with particulate concentration patterns during the sampling period. However, the regression models were based on a limited number of observations; therefore, these relationships should be interpreted as indicative trends rather than definitive causal effects.

Leaf Area Index (LAI)

The LAI values of the three vegetated plots are presented in Table 5. *Mimusops elengi* had the highest mean LAI value (2.1639), followed by *G. arborea* (1.8449) and *L. speciosa* (1.3048). Higher LAI values indicate greater leaf surface area per unit ground area, which may increase the opportunity for airborne particles to be intercepted by the canopy. The relatively high LAI of the *M. elengi*-dominated plot reflects its dense and compact canopy structure at the observed site.

Leaf Particulate Retention Capacity by Species

Leaf particulate retention capacity also differed among the observed species. *M. elengi* showed the highest mean particulate retention capacity, followed by *G. arborea* and *L. speciosa*. This result suggests

Table 4 Traffic volume during the sampling periods

Toll gate	Direction	Date	08:00–09:00	12:00–13:00	16:00–17:00
Cibubur 1	Exit (toward Bogor)	26 April 2025	1,220	1,215	1,384
		28 April 2025	1,381	1,533	1,542
		30 April 2025	1,194	1,052	1,462
GMU Cibubur	Entrance (toward Bogor)	26 April 2025	1,242	1,313	1,342
		28 April 2025	1,345	1,424	893
		30 April 2025	1,471	1,240	957
Combined Cibubur 1 + GMU Cibubur		26 April 2025	2,462	2,528	2,726
		28 April 2025	2,735	2,957	2,435
		30 April 2025	2,665	2,292	2,419

Table 5 Leaf Area Index (LAI) values of roadside vegetation

Vegetation species	Replication	Distance (m)	LAI value	Mean LAI
L.speciosa	1	0	1.2776	1.3048
		10	1.5342	
	2	0	1.2428	
		10	1.3874	
	3	0	1.4400	
		10	0.9469	
G. *arborea*	1	0	1.6296	1.8449
		10	1.9952	
	2	0	1.8668	
		10	1.9353	
	3	0	1.7607	
		10	1.8820	
M. elengi	1	0	2.0630	2.1639
		10	2.1917	
	2	0	2.1950	
		10	2.0657	
	3	0	2.3034	
		10	2.1645	

that the plot dominated by *M. elengi* had greater potential to retain particulate residue on leaf surfaces. The higher retention capacity may be related to leaf surface characteristics and canopy structure that support particle deposition. Plant species with rougher leaf surfaces, trichomes, wax layers, and denser canopies have been reported to capture more particulate matter because these characteristics provide greater surface complexity for particle adhesion and retention.

The percentage of leaf retention effectiveness in Table 6 should be interpreted separately from PM2.5 and PM10 reduction percentages. Leaf retention effectiveness represents the ability of leaf samples to retain particulate residue, whereas PM2.5 and PM10 reduction represent the decrease in airborne particulate concentration in vegetated plots compared with the non-vegetated control plot. This distinction is important because particulate retention at the leaf level does not directly represent the percentage reduction of airborne PM concentration at the plot level.

PM2.5 and PM10 Concentration Reduction Analysis

The measurement results showed that vegetated plots generally had lower PM2.5 and PM10 concentrations than the non-vegetated control plot. For PM2.5, the control plot had the highest mean concentration (35.29 µg/m³), while the plot dominated by *M. elengi* had the lowest mean concentration (22.50 µg/m³), followed by *G. arborea* (23.22 µg/m³) and *L. speciosa* (25.52 µg/m³). A similar pattern was observed for PM10. The control plot had the highest mean PM10 concentration (48.53 µg/m³), while the *M. elengi*-dominated plot showed the lowest mean concentration (31.59 µg/m³), followed by *G. arborea* (32.79 µg/m³) and *L. speciosa* (36.02 µg/m³).

The percentage reduction of PM2.5 and PM10 concentrations in vegetated plots compared with the control plot at the same sampling distances is presented in Figure 3a and Figure 3b. On average, vegetated plots reduced PM2.5 and PM10 concentrations by 30.82% and 29.23%, respectively,

Table 6 Leaf particulate retention capacity and leaf retention effectiveness

Species	Leaf code	Replication	Pollutant (mg)	Leaf area (cm²)	Particulate retention capacity (mg/cm²)	Leaf retention effectiveness (%)	Mean leaf retention effectiveness (%)
L. speciosa	A1	1	53.33	646.58	0.08	11.17	10.39
	A2	2	53.33	693.82	0.08	10.41	
	A3	3	50.00	705.66	0.07	9.59	
G. arborea	B1	1	80.00	821.06	0.10	13.19	10.53
	B2	2	60.00	846.90	0.07	9.59	
	B3	3	50.00	769.76	0.06	8.79	
M. elengi	C1	1	140.00	587.00	0.24	32.29	27.16
	C2	2	103.33	588.00	0.18	23.79	
	C3	3	110.00	586.57	0.19	25.39	

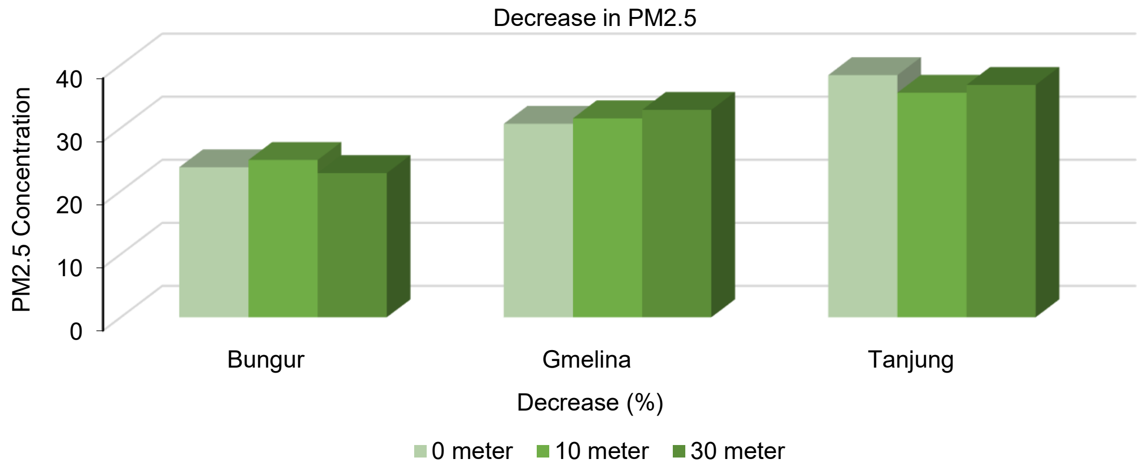


Figure 3a Percentage reduction of PM2.5 concentrations in vegetated plots compared with the non-vegetated control plot at the same sampling distances.

compared with the non-vegetated control plot. Among the vegetated plots, the plot dominated by *M. elengi* showed the largest average reduction, followed by *G. arborea* and *L. speciosa*. This pattern is consistent with the LAI and leaf retention results, where the *M. elengi*-dominated plot also showed the highest LAI and particulate retention capacity.

One-way ANOVA showed significant differences in particulate concentrations among plots (Table 7). PM2.5 concentrations differed significantly among plots, $F(3,32) = 64.641$, $p < 0.001$. Bonferroni post hoc tests indicated that the non-vegetated control plot differed significantly from all vegetated plots. Among vegetated plots, the plot dominated by *M. elengi* differed significantly from the plot dominated by *L. speciosa*, but did not differ significantly from the plot dominated by *G. arborea*. PM10 concentrations also differed significantly among plots, $F (3.32) = 44.755$, $p < 0.001$. For PM10, the control plot differed significantly from all vegetated plots, while the plots dominated by *G. arborea* and *M. elengi* were not significantly different from each other.

These results support the hypothesis that roadside greenbelt plots have lower PM2.5 and PM10 concentrations than non-vegetated areas. However, because the *M. elengi* and *G. arborea* plots were not significantly different from each other, the lower mean concentration in the *M. elengi*-dominated plot should be interpreted as the lowest observed average value rather than as evidence that *M. elengi* was statistically superior to all other species.

Influence of Environmental Variables on PM2.5 and PM10 Concentrations

Regression analysis was used to examine the relationship between particulate concentrations and environmental variables, including sampling distance, traffic volume, air temperature, relative humidity, and wind speed (Table 8a and Table 8b). Among these variables, traffic volume showed the highest R^2 values in most plots for both PM2.5 and PM10. This indicates that traffic activity was more strongly associated with particulate concentration than the observed microclimate variables during the sampling period.

The relationship between sampling distance and particulate concentration showed relatively low R^2 values in most plots. This suggests that particulate concentration did not decrease sharply across the 0, 10, and 30 m sampling points during the observation period. The limited distance effect may be influenced by local wind conditions, canopy arrangement, roadside topography, and the relatively short distance range used in this study. Microclimate variables, including temperature, relative humidity, and wind speed, generally showed low and inconsistent R^2

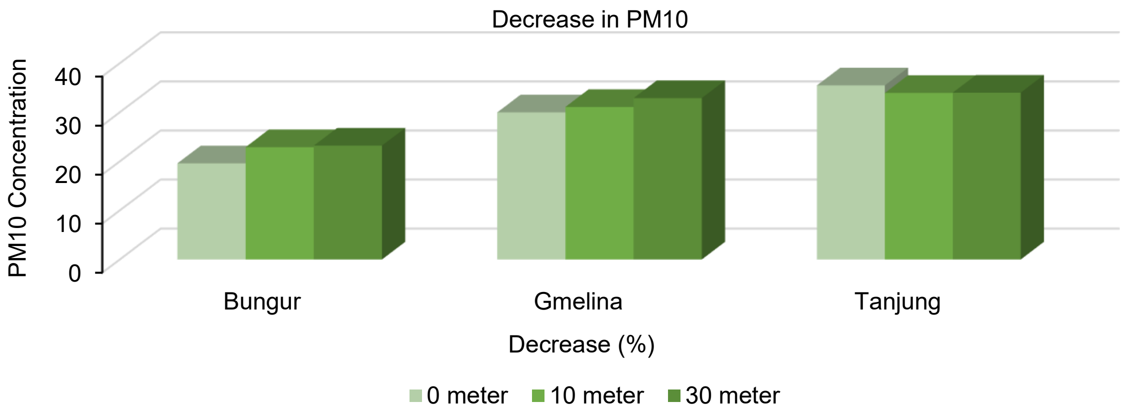


Figure 3b Percentage reduction of PM10 concentrations in vegetated plots compared with the non-vegetated control plot at the same sampling distances.

Table 7 One-way ANOVA and Bonferroni post hoc test results for PM2.5 and PM10 concentrations among plots

Parameter	Plot	n	Mean concentration (µg/m³)	ANOVA result	Post hoc group
PM2.5	Control	9	35.29	F(3,32) = 64.641; p < 0.001	a
	L. speciosa	9	25.52		b
	G. arborea	9	23.22		bc
	M. elengi	9	22.50		c
PM10	Control	9	48.53	F(3,32) = 44.755; p < 0.001	a
	L. speciosa	9	36.02		b
	G. arborea	9	32.79		c
	M. elengi	9	31.59		c

Note: Different letters within the same parameter indicate significant differences among plots based on Bonferroni post hoc test at p < 0.05.

Table 8a Regression analysis of environmental variables affecting PM2.5 concentrations

	PM 2.5							
Independent variable	Plot 1 (*L. speciosa*)	R^2	Plot 2 (*G. arborea*)	R^2	Plot 3 (*M. elengi*)	R^2	Control plot	R^2
Distance	y = −0.0310x + 26.910	0.0218	y = −0.0657x + 24.652	0.2627	y = −0.0241x + 22.255	0.0700	y = −0.0590x + 35.582	0.1028
Air temperature	y = −0.4057x + 40.197	0.0056	y = −0.2715x + 32.845	0.0077	y = −1.8316x + 82.240	0.1528	y = −1.1264x + 72.968	0.0165
Relative humidity	y = 0.0002x + 26.489	0.0000	y = 0.2149x + 10.968	0.0545	y = 0.2031x + 8.8974	0.0323	y = −0.1278x + 40.909	0.0080
Wind speed	y = −7.0326x + 32.183	0.0994	y = −3.9771x + 26.196	0.0340	y = 8.4170x + 17.921	0.1200	y = −5.9631x + 42.467	0.0859
Traffic volume	y = 0.0227x − 32.022	0.5185	y = 0.0205x − 29.067	0.5161	y = 0.0171x − 22.190	0.4663	y = 0.0301x − 43.783	0.5576

Table 8b Regression analysis of environmental variables affecting PM10 concentrations

	PM10							
Independent variable	Plot 1 (*L. speciosa*)	R^2	Plot 2 (*G. arborea*)	R^2	Plot 3 (*M. elengi*)	R^2	Control plot	R^2
Distance	y = −0.0960x + 38.388	0.0652	y = −0.0856x + 33.765	0.2373	y = −0.0176x + 31.344	0.0226	y = −0.0577x + 48.258	0.0524
Air temperature	y = 0.0617x + 35.027	0.0001	y = −0.3559x + 44.514	0.0069	y = −0.7708x + 56.490	0.0206	y = −2.6036x + 135.720	0.0442
Relative humidity	y = −0.1340x + 44.309	0.0139	y = 0.2955x + 15.006	0.0543	y = −0.0741x + 35.864	0.0033	y = −0.0276x + 48.812	0.0002
Wind speed	y = −8.4100x + 43.908	0.0654	y = −5.1559x + 35.760	0.0301	y = −7.5107x + 27.500	0.0727	y = −8.3994x + 58.296	0.0853
Traffic volume	y = 0.0324x − 46.473	0.4860	y = 0.0286x − 41.207	0.5313	y = 0.0233x − 29.006	0.6587	y = 0.0468x − 73.347	0.5250

values. These results suggest that microclimate conditions may have influenced particulate dispersion, but their effects were not dominant in the observed dataset.

Because the regression analysis was based on a limited sampling period and did not include p-values for each regression model, the results should be interpreted cautiously. The R^2 values describe the strength of association between variables, but do not necessarily indicate statistical significance or causal relationships. Therefore, the regression results are used to support the interpretation of particulate concentration patterns rather than to establish definitive predictive models.

Relationship between Leaf Particulate Retention Capacity and Particulate Concentration

The relationship between leaf particulate retention capacity and particulate concentration is shown in Figure 4. The regression results indicated a negative relationship between leaf particulate retention capacity and PM2.5 and PM10 concentrations. For PM2.5, the regression model showed R^2 = 0.4566, indicating that higher leaf particulate retention capacity was associated with lower PM2.5 concentration. For PM10, the relationship was weaker, with R^2 = 0.2914.

These results suggest that leaf particulate retention capacity contributed to particulate reduction, particularly for PM2.5. Leaf surfaces can retain particles through deposition, impaction, interception, and adhesion to surface structures. Species with greater retention capacity may therefore contribute to reducing airborne particulate concentrations near roadsides. However, leaf retention capacity alone does not fully explain particulate reduction because PM concentration is also affected by canopy structure, planting density, wind movement, and traffic emissions.

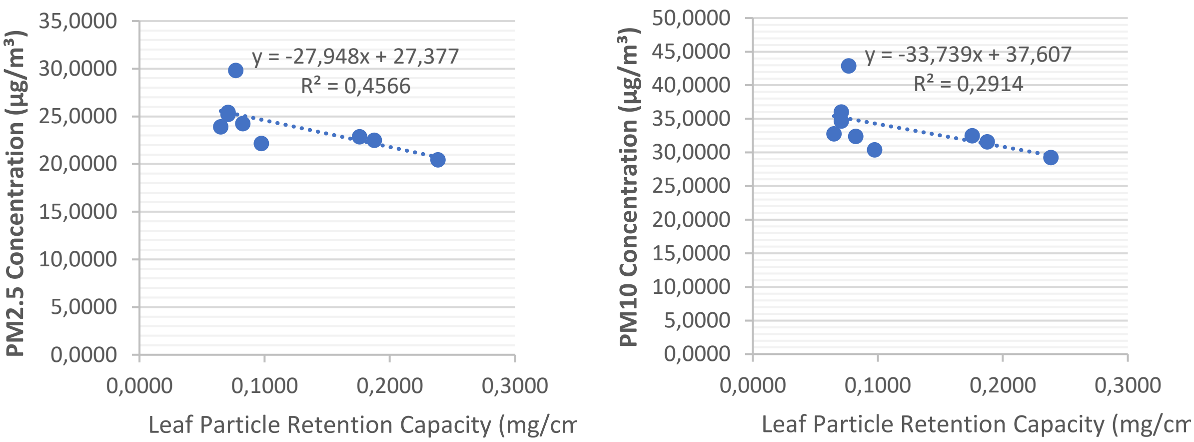
Relationship between Leaf Area Index and Particulate Concentration

The relationship between LAI and particulate concentration is presented in Figure 5. LAI showed a negative relationship with both PM2.5 and PM10 concentrations. The regression model for PM2.5 had $R^2 = 0.5162$, while PM10 had $R^2 = 0.4337$. These values indicate that LAI had a moderate association with particulate concentration, with higher LAI values corresponding to lower PM concentrations.

The stronger relationship between LAI and PM2.5 compared with PM10 suggests that denser canopy structure may be particularly important for reducing fine particles. A higher LAI provides a larger surface area for particle deposition and may increase the filtering function of roadside vegetation. These findings are consistent with previous studies indicating that canopy density, leaf area, and vegetation structure influence the ability of green infrastructure to reduce particulate matter in roadside environments.

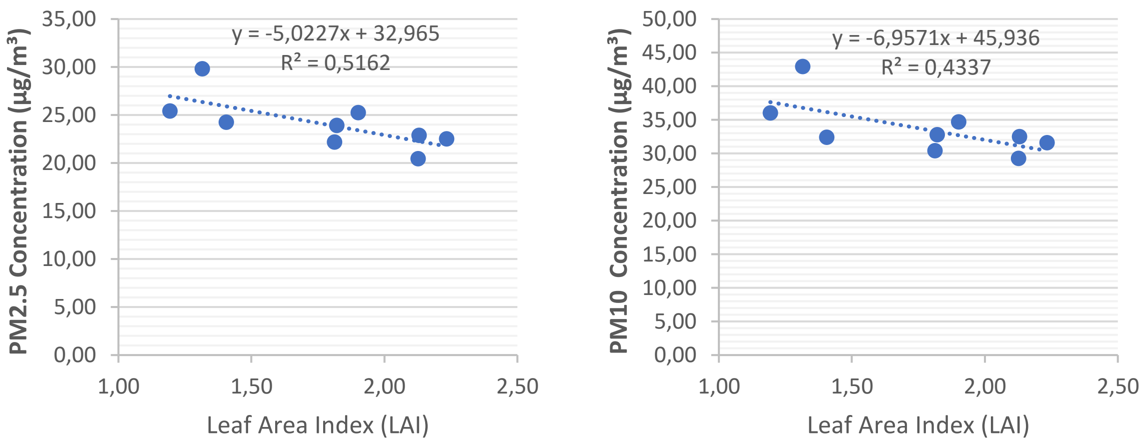
The relatively lower PM2.5 and PM10 concentrations observed in the *M. elengi*-dominated plot may be explained by the combined effects of canopy structure and leaf-level retention characteristics. This plot had the highest LAI value and a compact, continuous canopy, which may increase the contact surface between airborne particles and vegetation. A dense canopy can enhance particle interception by increasing leaf surface area and modifying airflow within the greenbelt. At the leaf level, particulate deposition is influenced by surface roughness, trichomes, wax layers, and leaf texture, which can increase the adhesion and retention of particles on leaf surfaces.

This mechanism is consistent with studies showing that vegetation characteristics such as canopy density, leaf surface complexity, and planting structure influence the ability of green infrastructure to capture particulate matter. Santunione *et al.* (2024) reported that particulate matter trapped by plant species varies



(a) (b)

Figure 4 Relationship between leaf particulate retention capacity (mg/cm²) and particulate concentration: (a) PM2.5 and (b) PM10.



(a) (b)

Figure 5 Relationship between leaf area index (LAI) and particulate concentration: (a) PM2.5 and (b) PM10.

according to plant characteristics and particle interaction with leaf surfaces. In the Indonesian roadside context, Hermawan (2012) also demonstrated the relevance of roadside vegetation structure in reducing particulate pollution along the Jagorawi Highway. Therefore, the results of the present study support the view that particulate mitigation by roadside greenbelts depends not only on the presence of trees, but also on canopy continuity, LAI, planting density, and leaf retention traits.

Overall, the results suggest that effective roadside greenbelt planning should consider both species characteristics and planting structure. High-LAI species with dense and continuous canopies may provide greater potential for PM2.5 and PM10 mitigation. Nevertheless, because each species in this study was represented by a single plot, the observed differences cannot be attributed solely to species identity. Instead, the results highlight the combined influence of dominant species, LAI, canopy density, planting arrangement, and site conditions on roadside particulate mitigation.

Limitations

The interpretation of this study should be placed within its sampling design and field conditions. Each dominant tree species was represented by one roadside greenbelt plot; therefore, the observed differences among plots reflect the combined influence of dominant species, planting structure, canopy density, topography, and local site conditions. This approach is useful for evaluating real roadside greenbelt conditions along the Jagorawi Toll Road, although further studies with replicated plots for each species would strengthen species-level comparisons. The sampling period was conducted over three observation days in April 2025, representing dry-season conditions. These data provide an initial understanding of PM2.5 and PM10 reduction under relatively stable field conditions; however, seasonal variation may influence particulate deposition and leaf surface retention, particularly during the rainy season when wash-off processes occur. Therefore, future studies should include longer sampling periods across dry and rainy seasons.

The digital air quality detectors used in this study were calibrated using LVAS, and the correction factor was applied to improve data comparability. Nevertheless, digital sensors may still be influenced by environmental conditions such as humidity, and detailed manufacturer accuracy or sensor response characteristics were not fully available. Therefore, the calibrated sensor data were interpreted cautiously. In addition, the regression analyses were based on a limited number of observations, so the R^2 values were used to indicate patterns of association rather than to establish definitive causal or predictive models. Future research should include replicated plots for each species, longer seasonal monitoring, and more detailed measurements of planting structure, canopy density, and leaf morphology. Such improvements would strengthen the understanding of how species characteristics and greenbelt structure jointly contribute to PM2.5 and PM10 mitigation along high-traffic road corridors.

CONCLUSION

This study shows that roadside greenbelt plots along the Jagorawi Toll Road had lower PM2.5 and PM10 concentrations than the non-vegetated control plot. On average, vegetated plots reduced PM2.5 and PM10 concentrations by 30.82% and 29.23%, respectively, compared with the control plot at the same sampling distances. The plot dominated by *Mimusops elengi* showed the lowest mean PM2.5 and PM10 concentrations and the largest average reduction, supported by the highest LAI value and leaf particulate retention capacity. However, the effect of species should be interpreted together with planting structure, canopy density, topography, and site conditions because each species was represented by one plot.

The results indicate that roadside greenbelts with dense and continuous canopies, higher LAI, and greater leaf particulate retention capacity have greater potential to reduce particulate concentrations near toll road corridors. Therefore, roadside greenbelt planning should prioritize high-LAI tree species, compact canopy structures, and multi-row planting arrangements, particularly along high-traffic road corridors. Future studies should include replicated plots for each species, longer sampling periods across seasons, and more detailed measurements of planting structure and leaf morphology to strengthen species-level conclusions.

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