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# Study of the Effectiveness of Patriot Bina Bangsa Urban Forest Bekasi City in Reducing $PM_{2.5}$ and $PM_{10}$ Pollutant Concentrations

Ridho Rio Handoko[a], Rachmad Hermawan[a], Nizar Nasrullah[b]

[a] Department of Forest Resources Conservation and Ecotourism, Faculty of Forestry and Environment, IPB University, Darmaga Campus, Bogor 16680, Indonesia

[b] Department of Landscape Architecture, Faculty of Agriculture, IPB University, Darmaga Campus, Bogor 16680, Indonesia

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## ABSTRACT

The population density and increasing number of vehicles in Bekasi City have the potential to increase air pollution, especially $PM_{2.5}$ and $PM_{10}$ concentrations in Bekasi City. This study aimed to analyze the effectiveness of the Patriot Bina Bangsa Urban Forest (PBB UF) in reducing the concentrations of $PM_{2.5}$ and $PM_{10}$ pollutants; measure the ability of leaves from dominant tree species in PBB UF to adsorb particulate pollutants; and analyze the impact of distance, vehicle emissions, Leaf Area Index (LAI), speed, and wind direction on reducing $PM_{2.5}$ and $PM_{10}$ concentrations in PBB UF, Bekasi City. The research was conducted using field observations, gravimetry, and literature studies. The effectiveness of Patriot Bina Bangsa Urban Forest in reducing $PM_{2.5}$ concentration was 14.40% while $PM_{10}$ was 20.81%. A three-week study of dust absorption by the leaves of the broad-leaved mahogany (*Swietenia macrophylla*) showed that the leaves' ability to absorb dust increased each week. The average ability of leaves to adsorb daily dust was 14,192.23 $\mu g/cm^2$, with the largest percentage decrease occurring at a distance of 0–10 m (43.07 %). Dust absorption capacity decreases as the distance from the dust source increases. It is suspected that vehicle emissions are the most dominant variable influencing $PM_{2.5}$ and $PM_{10}$ concentrations in PBB UF.

## Introduction

Air pollution is a global threat that has a serious impact on health, especially in children and the elderly. Particulate Matter (PM) is the most significant air pollutant because it can cause cardiovascular disease, respiratory disorders, and cancer [1]. Early exposure to PM pollutants can permanently damage body tissues [2] and weaken the immune system [3]. The health effects can include short-term effects, such as irritation and headaches, as well as long-term effects, including reduced lung function and an increased risk of cancer [2]. The presence of these particles is one of the main causes of health problems affecting the human respiratory system [4]. Because of its extremely small size, $PM_{2.5}$ can penetrate deep into the lungs, bypass the gas exchange area, pass through the respiratory barrier, and enter the bloodstream. Thus, $PM_{2.5}$ can spread throughout the body via the blood [5]. In Bekasi City, this problem is exacerbated by high population density and the number of vehicles, with the transportation sector being the dominant contributor to air pollution in large cities, reaching 60-70% [6]. As a solution to urban environmental degradation, the presence of urban forests is important because trees are a key factor in the quality of life [7].

Vegetation can reduce pollution through the absorption and uptake of pollutants by plant tissues. Research has proven that green belts are effective in reducing $PM_{2.5}$ and $PM_{10}$ concentrations [8], and trees with large leaves, rough surfaces, and dense canopies have been proven to be most effective in reducing dust dispersion [9]. Greening efforts are a recognized method of controlling pollutants [10]. Various studies have been conducted on the role of vegetation in reducing air pollution in urban areas in Indonesia, such as NOx and CO

**Corresponding Author:** Rachmad Hermawan rachmadhe@apps.ipb.ac.id Department of Forest Resources Conservation and Ecotourism, Faculty of Forestry and Environment, IPB University, Darmaga Campus, Bogor 16680, Indonesia

gas pollutants [11]. Previous research has discussed the role of green belts in reducing $PM_{2.5}$ and $PM_{10}$ particulate matter on elevated highways [8]. Studies on the role of urban forests in Indonesia in reducing PM2.5 and PM10 particulate matter in urban areas remain limited. There has been no in-depth study examining the effectiveness of the Patriot Bina Bangsa Urban Forest (PBB UF) in Bekasi City in reducing $PM_{2.5}$ and $PM_{10}$; therefore, this study is needed to make an important contribution to effective green planning. The PBB UF in Bekasi serves as an apt example of the role that urban forests play in areas with high population density and heavy vehicle traffic. The high number of vehicles and dense population in Bekasi contribute to increased air pollution. According to data from the Central Statistics Agency [12], there are 101,644 vehicles in Bekasi, Indonesia. By vehicle type, Bekasi City is dominated by motorcycles and minibuses, with numbers reaching 80,704 and 16,739 units, respectively. According to BPS projections, Bekasi City's population in 2024 is estimated to reach 2,644,058 people. The population density in Bekasi City has increased alongside the growing population. Bekasi City has a relatively high population density with a total area of 213.12 km². Of the 12 sub-districts, nine have a population density exceeding 10,000 people per km².

This study had three main objectives. First, we analyzed the effectiveness of the Patriot Bina Bangsa Urban Forest in Bekasi City in reducing $PM_{2.5}$ and $PM_{10}$ pollutant concentrations. Second, this study measured the ability of leaves from the dominant tree species at the location to absorb particulate pollutants. Third, it was also to analyze the influence of various factors such as distance, estimated vehicle emissions, Leaf Area Index (LAI), and wind speed and direction on the reduction of the concentrations of these two pollutants in the Patriot Bina Bangsa Urban Forest.

## Materials and Methods

### Research Location

The study will be conducted from December 2024 to June 2025. The study was conducted at the Patriot Bina Bangsa Urban Forest (PBB UF) in Bekasi City, at Jalan Ahmad Yani Street No. 2, RT.004/RW.016, Kayuringin Jaya, South Bekasi District, Bekasi City, West Java, Indonesia. The observation site was divided into two plots with air sampling points in the vegetated and open areas. Air samples were collected around Ahmad Yani Street as the polluting location under clear weather conditions.

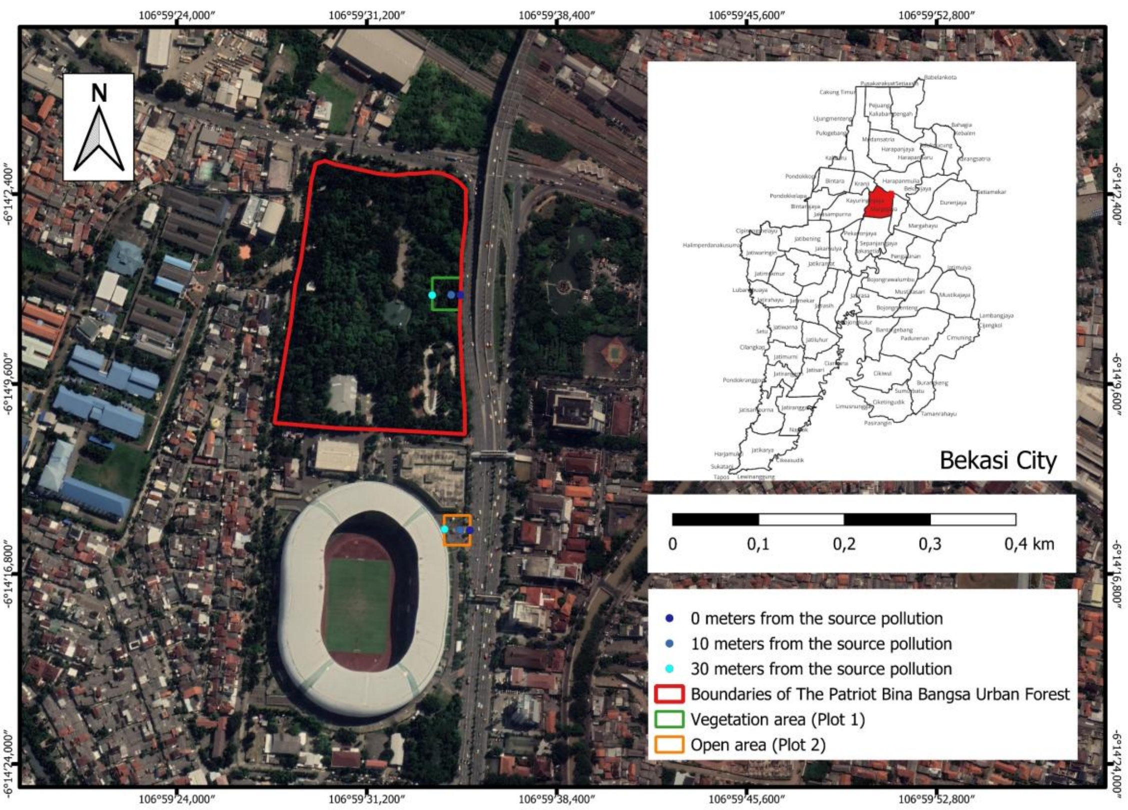


**Figure 1.** Map of the study area used to compare vegetated and open areas in terms of their ability to reduce concentrations of particulate matter (modified from Google Earth 2023).

**Tools and Materials**

The equipment used in this study included A Dienmern brand digital air quality detector (model DM-72B), conventional low-volume air sampler (LVAS) with a nominal flow rate of 5 L/min, hygrometer, smartphone camera, digital single-lens reflex (DSLR) camera, fisheye lens, tally counter, anemometer, mini digital weather station, pruner, brush, beaker, oven, portable area meter, digital scale, and laptop. The air quality detector used was a Dienmern brand model DM-72B. The materials used included brown envelopes and distilled water.

**Data Collection**

This study used two types of data: primary and secondary. The primary data included $PM_{2.5}$ and $PM_{10}$ concentrations at the study site, traffic volume, Leaf Area Index (LAI), climate data, and the particle absorption capacity of leaves. Measurements of leaf absorption capacity were conducted over three consecutive weeks, with data collected weekly. Meanwhile, the collection of other data was carried out simultaneously during the period of March 19–22, 2025. On each observation day, sampling was conducted at three time intervals: 8:00–9:00 AM, 12:00–1:00 PM, and 4:00–5:00 PM.

***Measurement of $PM_{2.5}$ and $PM_{10}$ concentrations for calibration***

To ensure the validity and accuracy of the $PM_{2.5}$ and $PM_{10}$ concentration measurements, the instruments were calibrated beforehand. The calibration site was deliberately chosen on Jalan Raya Dramaga because of its heavy traffic, which provided representative conditions for testing the instrument performance. Instrument calibration aims to compare and align the measurement results obtained from the digital air quality detector with those from the standard instrument, namely, the LVAS. The operation of the LVAS is carried out through several systematic steps, ranging from stabilizing the filter inside the desiccator and measuring the initial mass of the filter to taking five air samples, each lasting one hour at a constant flow rate of 10 liters per minute. Once the sampling process was complete, the filter was returned to the desiccator for stabilization prior to final weighing. The mass of the collected particulate matter was then determined gravimetrically and subsequently analyzed further in the laboratory [13]. During the sampling process, the digital detector automatically recorded the particle concentrations every 10 min. The collected data were then averaged and compared with the measurement results from the LVAS to evaluate the accuracy of the digital instrument and determine the correction factors required for the calibration process.

***Measurement of $PM_{2.5}$ and $PM_{10}$ concentrations at the research site***

Measurements of $PM_{2.5}$ and $PM_{10}$ concentrations in the field were conducted at two different types of locations, namely vegetated areas and open areas that served as controls. At each location, data were collected at three specific distances: 0 m (right at the edge of the nearest urban forest from the road), 10 m, and 30 m. The measurement schedule was designed to represent the weekday (Wednesday, Thursday, and Friday) and weekend (Saturday) conditions. Each day, measurements were taken in three-time sessions to capture variations in traffic activity, namely in the morning (08:00–09:00 AM), afternoon (00:00–01:00 PM), and evening (04:00–05:00 PM) using a digital air quality detector.

***Vehicle volume and vehicle emission estimation***

Traffic volume data on Ahmad Yani Street were collected using video recordings taken concurrently with air sampling. From these recordings, the team manually counted the number of vehicles using a hand counter. This process occurred over three time periods spread across a four-day span. Finally, all passing vehicles were categorized by fuel type: gasoline and diesel.

***Leaf area index (LAI)***

Canopy density in vegetated areas is analyzed by measuring the Leaf Area Index (LAI), which is the ratio of leaf area to total land area. In practice, this parameter is measured using a DSLR camera equipped with a fisheye lens [14]. The precise LAI values in this study were obtained by analyzing canopy photographs using Hemiview 2.1 software. Visual data were collected from nine points within a 40 m × 30 m plot positioned at distances of 0, 10, and 30 m from the pollution source.

***Microclimate measurement***

Local weather conditions were monitored through microclimate measurements to record specific data, including air temperature, humidity, wind speed, and direction. These parameters are crucial because they directly affect the dynamics of air pollutant concentrations. Field data were collected at three monitoring points located 0, 10, and 30 m from the pollution source. To ensure the validity of the results, instruments such as hygrometers, anemometers, and digital mini weather stations were configured to automatically record data every 10 min.

***Sampling of air pollution absorption on leaves***

This study used a total of nine sample trees that were purposively selected based on strict criteria, namely, trees of the same species (such as *Swietenia macrophylla*), uniform height, and even distribution. *Swietenia macrophyla* was selected as the subject of this study because it was consistently present at the observation sites. In addition, the species dominates the boundary between the highway and urban forest area, making it crucial to assess its role in reducing vehicle pollution from the highway. The trees were grouped into three rows based on their distance from the emission source (0, 10, and 30 m), with three trees as replicates for each distance category. Leaf samples were collected once a week for three consecutive weeks, resulting in 27 dust sample units. To maintain consistent environmental conditions, 20-gram samples from each tree were collected simultaneously in the morning (07:00–08:00 AM) from the middle of the canopy (3–5 m high) facing the road. The selected leaves had to meet specific requirements according to Sukarsono [15]: healthy, perfectly green, free from pests or diseases, and located in the second or third position from the tip of the branch. The plants were then cut using pruners and stored in brown envelopes for further analysis.

***Determination of correction factors and corrected pollutant concentration values***

To calibrate the accuracy of digital air quality monitors, a correction factor is required to obtain valid concentration values. This correction factor was calculated based on a comparison of the measurement results from the LVAS and the digital monitor as described in Equation 1.

$$\text{Correction factor}= \frac{\text{LVAS Device Concentration Value}}{\text{Concentration Air Quality Detector Device}r} \quad (1)$$

The correction factor was used to determine the corrected concentration using the following formula as described in Equation 2.

$$\text{Corrected concentration} = \text{Initial concentration} \times \text{Correction factor} \quad (2)$$

***Analysis of the effectiveness of urban forests in reducing $PM_{2.5}$ and $PM_{10}$ pollutant concentrations***

The effectiveness of urban forests in reducing pollutants was measured using specific distances. This variable distance helps to show how well trees can filter polluted air. In this study, three field measurement distances were used: 0, 10, and 30 m from the source. Field data from these points were used to calculate the percentage decrease in pollutant concentration. The percentage was calculated using the following formula as described in Equation 3.

$$\text{Percentage(\%)} = \frac{\text{Average PM (0 Meters) - Average PM (30 Meters)}}{\text{Average PM (0 Meters)}} \times 100\% \quad (3)$$

The effectiveness calculation uses the following formula as described in Equations 4.

$$\text{Reduction in pollutants in vegetated areas (\%)} - \text{reduction in pollutants in open areas (\%)} \quad (4)$$

***Vehicle emission estimation***

To ensure data accuracy, the volume of vehicles passing through Ahmad Yani Street was documented using a 15-minute video recording method. During the counting process, the vehicles were categorized based on their fuel type, namely gasoline and diesel. This classification is crucial in air quality studies, given that each fuel type emits different types of particles into the surrounding environment.

To quantify total emissions, the recorded vehicle counts were converted into total mass emissions per kilometer traveled in accordance with standard approaches [9], The estimation differentiated between gasoline- and diesel-powered vehicles to account for their distinct particulate emission profiles. Equations 5 and 6 express the mathematical formulation used to quantify total emissions for gasoline and solar (diesel) vehicles, respectively.

$$\text{Gasoline vehicle emissions} = \text{vehicle volume (gasoline)} \times \frac{100}{1000} \times 0.22 \frac{\text{g}}{\text{km}} /\text{vehicle} \quad (5)$$

$$\text{Solar vehicle emissions} = \text{vehicle volume (solar)} \frac{100}{1000} \times 1.28 \frac{\text{g}}{\text{km}} /\text{vehicle} \quad (6)$$

To determine the overall air pollution burden from the observed traffic flow, the individual emission values from both vehicle types were aggregated. This cumulative emission rate represents the combined particulate contribution from both gasoline- and diesel-fueled vehicles along the studied corridor. The total vehicle emissions were calculated by summing the specific emission estimates, as formulated in Equation 7.

$$\text{Total Emissions} = \text{Vehicle Emissions (Gasoline)} + \text{Vehicle Emissions (solar)} \quad (7)$$

***Analysis of the ability of leaves to absorb dust***

The analysis process in the laboratory began with determining the dust content in the leaf samples using the gravimetric method. First, the leaves were washed in a beaker containing 60 ml of distilled water, which was weighed beforehand to remove all dust particles. Next, the wash water in the beaker was completely evaporated using an oven at 80°C for 48 h until only dry dust residue remained. The total mass of dust was then calculated from the difference between the final weight (beaker + dust) and the initial weight of the beaker. After washing, the total surface area of the same leaf sample was accurately measured in cm² using a portable area meter. In the final stage, the ability of the leaves to absorb dust was calculated by dividing the total mass of dust collected by the total surface area of the leaves that has been measured. The estimation of particle absorption capacity by the Patriot Bina Bangsa Urban Forest (PBB UF) was conducted through a series of step-by-step calculations. This process began with estimating the total number of trees by dividing the total forest area, which is 3 ha (30,000 m²), assuming a planting distance of 6x6 meters. Next, the total crown area was calculated by multiplying the number of trees by the individual crown area, which was assumed to have a diameter of 6 m. The shape of the tree canopy was assumed to be spherical; therefore, the surface area of a single tree canopy was calculated using Equations 8.

$$\text{The area of one tree canopy} = 4 \times \pi \times r^2 \quad (8)$$

Following the determination of the individual canopy dimensions, the cumulative crown surface area for the entire forest stand was calculated. This step integrates the spatial footprint of individual trees to evaluate the total vegetative surface available for atmospheric particle interception across the urban forest. The total canopy area was quantified by multiplying the single-tree canopy area by the total estimated tree population, as formulated in Equation 9.

$$\text{The area of one tree canopy} = 4 \times \pi \times r^2 \quad (9)$$

The daily pollutant absorption capacity was estimated by multiplying the total crown area calculated by the average particle absorption value obtained from empirical measurements, which was 14,192.23 µg/cm² per day. In the final stage, the total daily absorption capacity was compared with the estimated total vehicle emissions. This emission calculation uses the assumption that nighttime emissions are 30% of daytime emissions due to minimal mobility, thereby obtaining the percentage of vehicle pollution that can be mitigated by urban forests. The total percentage of urban forest absorption compared to total emissions was calculated using Equations 10.

$$\text{Percentage of absorption} = \left(\frac{\text{Total urban forest absorption/day}}{\text{Total estimated vehicle emissions/day}}\right) \times 100\% \quad (10)$$

***Independent Sample T-test Analysis and Simple Linear Regression***

Statistical data analysis in this study used two main methods. The comparison of $PM_{2.5}$ and $PM_{10}$ concentration levels between the two observation areas was tested using an independent samples t-test. In addition to comparing the two locations, this study also measured the extent to which external factors, such as distance, LAI, wind speed, and vehicle emissions, influenced fluctuations in PM concentrations using linear regression analysis. All statistical processing was performed using IBM SPSS 24, where the strength of the relationship between variables was analyzed in depth using the correlation coefficient (Multiple-R) (Table 1).

**Table 1.** Guidelines for interpreting correlation coefficients to understand the extent to which distance from emission sources, wind speed, estimated vehicle emissions, and LAI influence $PM_{2.5}$ and $PM_{10}$ concentrations at the study site [16].

| Coefficient Interval | Relationship Level |
|---|---|
| 0.00 – 0.199 | Very Low |
| 0.20 – 0.399 | Low |
| 0.40 – 0.599 | Moderate |
| 0.60 – 0.799 | Strong |
| 0.80 – 1.00 | Very Strong |

## Results and Discussion

### Result

#### *General condition*

The study site was located in the Patriot Bina Bangsa (PBB UF) Urban Forest in Bekasi City, specifically along Ahmad Yani Street. To obtain comparative data, observations were conducted at two points: a vegetated area within the urban forest and an open area across from it, in front of the Patriot Candrabhaga Stadium. These two locations were deliberately chosen because they were aligned with the primary emission sources. The functions of PBB UF itself are regulated by Bekasi Mayor's Decree No. 032/Kep.459-BPKAD/XI/2012, which designates it as a water catchment area, gene bank, tourist destination, and community activity center. From an ecological perspective, the Patriot Bina Bangsa Urban Forest (HUT PBB) has a rich and diverse array of vegetation. Uniquely, the stand structure in this three-hectare forest is divided based on the dominance of plant families. In the seedling and sapling phases, plant species from the Fabaceae family were the most dominant. Conversely, as plants enter the pole and tree stages, dominance shifts to the Moraceae family. Given its large area, this site serves as the largest and most vital green public space for the residents of Bekasi City [17].

Tree canopy density has been shown to have a direct impact on the surrounding microclimate. This is evident from the significant differences between areas with dense and sparse canopies. Areas with dense canopy cover maintained a lower ambient temperature, averaging 27.6°C, with humidity reaching 80.1%. Conversely, in areas where the tree canopy is sparse, macroclimatic conditions become hotter and drier, characterized by a temperature spike of 30.1°C and a drop in humidity to 70.5% [18]. These findings reinforce the evidence regarding the crucial ecological role of vegetation, not only in stabilizing the microclimate but also in improving the urban air quality. In addition to its environmental contributions, PBB UF plays a significant role in the social sphere. This area has transformed into a dynamic public space for local residents, ranging from a sports center and recreational area to a venue for ceremonies and a hub for the local economy through a weekly flea market [19]. The supporting infrastructure in this area is designed to meet both recreational and educational needs. For residents looking to engage in physical activity, there are basketball courts, jogging trails, and fitness facilities available. As for recreational and educational needs, the management has provided gazebos, a children's play area, and vegetation information boards documenting at least 72 plant species found on-site [20]. However, security improvements are still needed to enhance public comfort and safety.

#### *Microclimate conditions at the research site*

Sampling of $PM_{2.5}$ and $PM_{10}$ concentrations was deliberately conducted on clear days from morning to afternoon. To ensure data accuracy, this field study was strictly scheduled for the dry season, specifically when the study area received no rainfall for a full week prior to the measurements. This dry condition was important, although rain sometimes occurred in March. Simultaneously, measurements of local microclimate conditions were carefully recorded at both research sites. The recorded weather parameters included detailed data on air humidity, temperature, wind speed, and wind direction (Table 2).

**Table 2.** Microclimatic parameters recorded across different sampling times at the study site. The table presents diurnal measurements of average air humidity (%), air temperature (°C), wind speed (m/s), and dominant wind direction observed during the dry season sampling period in March 2025. These microclimatic data characterize the baseline ambient conditions during the $PM_{2.5}$ and $PM_{10}$ monitoring.

| Plot | Sampling Time | Microclimate | | | |
|---|---|---|---|---|---|
| | | Average air humidity (%) | Average air temperature (°C) | Average wind speed (m/s) | Dominant wind direction (Blowing to) |
| Plot I (Vegetation area) | Wednesday, March 19, 2025 | | | | |
| | 08:00–09:00 AM | 80.05 | 27.73 | 1.09 | North |
| | 00:00–01:00 PM | 67.19 | 30.55 | 0.90 | Northwest |
| | 04:00–05:00 PM | 76.28 | 30.04 | 0.78 | Northwest |
| | Thursday, March 20, 2025 | | | | |
| | 08:00–09:00 AM | 76.28 | 30.17 | 0.91 | West |
| | 00:00–01:00 PM | 70.19 | 31.78 | 0.82 | West |
| | 04:00–05:00 PM | 69.91 | 30.41 | 0.99 | West |

| Plot | Sampling Time | Microclimate | | | |
|---|---|---|---|---|---|
| | | Average air humidity (%) | Average air temperature (°C) | Average wind speed (m/s) | Dominant wind direction (Blowing to) |
| | Friday, March 21, 2025 | | | | |
| | 08:00–09:00 AM | 69.90 | 30.38 | 1.11 | West |
| | 00:00–01:00 PM | 60.52 | 32.40 | 1.13 | West |
| | 04:00–05:00 PM | 64.52 | 31.19 | 0.90 | West |
| | Saturday, March 22, 2025 | | | | |
| | 08:00–09:00 AM | 74.76 | 29.54 | 1.07 | West |
| | 00:00–01:00 PM | 68.57 | 31.66 | 1.12 | West |
| | 04:00–05:00 PM | 73.62 | 29.77 | 0.89 | Southwest |
| Plot II (Open area) | Wednesday, March 19, 2025 | | | | |
| | 08:00–09:00 AM | 47.35 | 34.55 | 1.68 | Southwest |
| | 00:00–01:00 PM | 35.43 | 37.38 | 1.51 | West |
| | 04:00–05:00 PM | 46.65 | 35.27 | 1.29 | West |
| | Thursday, March 20, 2025 | | | | |
| | 08:00–09:00 AM | 58.81 | 32.61 | 1.58 | West |
| | 00:00–01:00 PM | 48.33 | 35.17 | 1.46 | Northwest |
| | 04:00–05:00 PM | 48.62 | 33.21 | 1.40 | West |
| | Friday, March 21, 2025 | | | | |
| | 08:00–09:00 AM | 39.19 | 36.09 | 1.53 | Southwest |
| | 00:00–01:00 PM | 33.05 | 37.81 | 1.37 | Southwest |
| | 04:00–05:00 PM | 42.43 | 35.60 | 1.46 | West |
| | Saturday, March 22, 2025 | | | | |
| | 08:00–09:00 AM | 51.91 | 33.85 | 1.26 | West |
| | 00:00–01:00 PM | 45.29 | 36.80 | 1.67 | Northwest |
| | 04:00–05:00 PM | 43.24 | 32.92 | 1.41 | West |

Average microclimate in the vegetation area on weekdays: humidity 70.54%, air temperature 30.52 °C, wind speed 0.92 m/s. Meanwhile, the average microclimate in open areas on weekdays was: humidity 44.43%, air temperature 35.30 °C, and wind speed 1.48 m/s. Observations showed that The average air humidity in vegetated areas was higher than that in open areas, whereas the air temperature in open areas was higher than that in vegetated areas. This difference indicates an inverse relationship between temperature and air humidity and confirms that vegetation can lower temperatures through evapotranspiration and increase air humidity in the surrounding area. Meanwhile, the wind speed in open areas was recorded to be higher than that in vegetated areas, indicating that trees in the PBB UF act as natural windbreaks. The diverse vegetation structure, both in terms of tree type and size, forms a rougher canopy surface that is effective in blocking wind flow [21]. Coarse-leaved tree species, such as *Acacia* sp., *Swietenia mahagoni*, *Gmelina arborea*, and *Ficus benjamina*, are known to be efficient in resisting wind speeds. This finding is in line with Todd et al. [22] research, which states that an increase in the roughness of the vegetation canopy profile reduces wind speeds beneath it.

The prevailing wind direction at the research site was recorded as moving west, southwest, and northwest, with a blowing pattern or the direction of air mass movement. This pattern indicates that the wind moved from the emission source on Ahmad Yani Street towards vegetated areas, known as the downwind direction. The impact of the conditions prevailing during the observation session was evident in the movement and dispersion of pollutants. Pollutant particles travel from the source area to forested areas, which play a crucial ecological role as both sinks and filters for airborne particulates.

***Traffic volume and estimated emissions***

Traffic volume data were obtained from video recordings taken at the research site. These videos were recorded simultaneously with the observations of $PM_{2.5}$ and $PM_{10}$. The total number of vehicles was calculated based on 15-minute recordings per session. This number was then converted to an hourly volume by multiplying the 15-minute count by four. Finally, the traffic observations covered two directions, namely the northbound lane (Lane A) and the southbound lane (Lane B) as presented in Table 3.

**Table 3.** Hourly traffic volume categorized by vehicle class observed along Ahmad Yani Street. The table details the hourly count of motorcycles, Class I motor vehicles (non-bus and bus), and heavy vehicles (Classes II, III, IV, and V) across specified observation sessions from March 19 to March 22, 2025. These traffic counts were derived from 15-minute video recording sessions scaled to hourly values and serve as the baseline data for estimating traffic-generated particulate matter emissions.

| Observation Time | Motorcycle | Motor vehicle | | |
|---|---|---|---|---|
| | | Class I | | Class II,III,IV,V |
| | | Non-Bus | Bus | |
| Wednesday, March 19, 2025 | | | | |
| 08:00 – 09:00 AM | 7,656 | 4,780 | 72 | 784 |
| 00:00 – 01:00 PM | 7,028 | 5,212 | 32 | 936 |
| 04:00 – 05:00 PM | 10,288 | 5,484 | 96 | 684 |
| Thursday, March 20, 2025 | | | | |
| 08:00 – 09:00 AM | 15,728 | 5,148 | 104 | 456 |
| 00:00 – 01:00 PM | 8,028 | 5,772 | 76 | 816 |
| 04:00 – 05:00 PM | 8,828 | 5,444 | 104 | 472 |
| Friday, March 21, 2025 | | | | |
| 08:00 – 09:00 AM | 12,368 | 5,108 | 140 | 504 |
| 00:00 – 01:00 PM | 8,704 | 8,660 | 68 | 808 |
| 04:00 – 05:00 PM | 10,520 | 6,132 | 100 | 744 |
| Saturday, March 22, 2025 | | | | |
| 08:00 – 09:00 AM | 18,316 | 3,560 | 96 | 928 |
| 00:00 – 01:00 PM | 13,628 | 6,240 | 140 | 984 |
| 04:00 – 05:00 PM | 13,884 | 7,388 | 132 | 644 |

Average number of vehicles on Ahmad Yani Street on weekdays: 9,905 motorcycles, 5,748 non-buses, 88 buses, and 682 vehicles of classes II, III, IV, and V. Vehicles traveling on Ahmad Yani Street consist of motorcycles, cars, jeeps, pickups, buses, and trucks with 2–4 axles. Class I vehicles generally run on gasoline, whereas Classes II–V, which are dominated by trucks, use diesel fuel. The details of the number of vehicles and estimated emissions are presented in Table 4.

**Table 4.** Estimated vehicular emissions grouped by fuel type during specified observation sessions on Ahmad Yani Street. The table presents calculated total particulate emission rates (g/km/vehicle) originating from gasoline-powered vehicles, diesel-fueled vehicles, and their combined total across different sampling time slots in March 2025. These estimates illustrate the relative contribution of each fuel class to the ambient pollutant load along the monitored road corridor.

| Observation Time | Emissions Estimates | | |
|---|---|---|---|
| | Total Emissions from Gasoline-Powered Vehicles (g/km/vehicle) | Total Emissions from Diesel-Fueled Vehicles (g/km/vehicle) | Total Emissions (g/km/vehicle) |
| Wednesday, March 19, 2025 | | | |
| 08:00–09:00 AM | 273.59 | 109.57 | 383.16 |
| 00:00–01:00 PM | 269.28 | 123.90 | 393.18 |
| 04:00–05:00 PM | 346.98 | 99.84 | 446.82 |
| Thursday, March 20, 2025 | | | |
| 08:00–09:00 AM | 459.27 | 71.68 | 530.95 |
| 00:00–01:00 PM | 303.60 | 114.18 | 417.78 |
| 04:00–05:00 PM | 313.98 | 73.73 | 387.71 |

| Observation Time | Emissions Estimates | | |
|---|---|---|---|
| | Total Emissions from Gasoline-Powered Vehicles (g/km/vehicle) | Total Emissions from Diesel-Fueled Vehicles (g/km/vehicle) | Total Emissions (g/km/vehicle) |
| Friday, March 21, 2025 | | | |
| 08:00–09:00 AM | 384.47 | 82.43 | 466.90 |
| 00:00–01:00 PM | 382.01 | 112.13 | 494.14 |
| 04:00–05:00 PM | 366.34 | 108.03 | 474.38 |
| Saturday, March 22, 2025 | | | |
| 08:00–09:00 AM | 481.27 | 131.07 | 612.34 |
| 00:00–01:00 PM | 437.10 | 143.87 | 580.97 |
| 04:00–05:00 PM | 467.98 | 99.33 | 567.31 |

The average estimated vehicle emissions on Ahmad Yani Street on weekdays were as follows: gasoline-powered vehicles at 344.39 g/km/vehicle, diesel-powered vehicles at 99.50 g/km/vehicle, and total emissions at 440.08 g/km/vehicle. The estimated emission values were calculated by multiplying the number of vehicles by the emission coefficient according to the fuel type, namely, 0.22 for gasoline-fueled vehicles and 1.28 for diesel-fueled vehicles [9]. The results showed that the highest emissions occurred on Saturdays between 8:00 and 9:00 AM., whereas the lowest emissions were recorded on Wednesdays at the same time. The high emissions on Saturdays were due to the increased vehicle volume, especially diesel-fueled vehicles, which contribute more to the formation of pollutant particles than gasoline-fueled vehicles [23].

***Leaf Area Index (LAI)***

The Leaf Area Index (LAI) was carefully determined for each vegetated plot. This parameter was measured at three different distances from the emission source, specifically at 0, 10, and 30 meters. To ensure the validity and reliability of the data collected, the field team repeated the measurements three times at each distance. The LAI values were obtained from a detailed analysis of fish-eye photos using the Hemiview 2.1 application. This software calculates the index by comparing the total leaf surface area to a single unit of land area. The measurement results are presented in Table 5.

**Table 5.** Leaf Area Index (LAI) values measured at varying distances from the roadside emission source. The table presents three measurement repetitions and the corresponding mean LAI values determined at 0, 10, and 30 meters from the road edge using Hemiview 2.1 software analysis of hemispherical photographs. These data illustrate the spatial gradient in canopy density and overall vegetative surface area across the urban forest buffer zone.

| Distance Plot | Repetition | | | Average LAI |
|---|---|---|---|---|
| | 1 | 2 | 3 | |
| 0 Meters | 1.77 | 1.55 | 1.44 | 1.59 |
| 10 Meters | 2.31 | 2.66 | 2.33 | 2.43 |
| 30 Meters | 2.18 | 2.51 | 2.65 | 2.45 |
| Average Vegetation LAI | | | | 2.16 |

The highest Leaf Area Index (LAI) values were recorded at a distance of 30 m from the roadside, whereas the lowest were observed at 0 m, where canopy cover was limited due to proximity to the road–vegetation boundary. LAI values increased between 10 and 30 m, corresponding to the presence of large tree species, such as *Bauhinia purpurea*, *Mimusops elengi*, *Swietenia macrophylla*, *Tectona grandis*, and *Gmelina arborea*. The similarity in LAI values at 10 and 30 m indicates a comparable canopy density and the existence of a multilayered canopy structure within the PBB UF, extending from the understory to the upper tree layer.

***Particle absorption on leaf***

Particle deposition on the leaves was observed carefully over a period of three weeks. Leaf samples were collected on a regular weekly schedule every Tuesday. These samples were taken from broad-leaved mahogany trees (*Swietenia macrophylla*) at the research site. This specific tree species was easily found throughout all observation distances, including 0 m, 10 m, and 30 m from the source. Furthermore, these mahogany trees were chosen because they were the dominant vegetation species in the PBB UF area (Table 6).

**Table 6.** Daily particle absorption capacity of mahogany (Swietenia macrophylla) leaves across different observation dates and distances. The table details the weekly measurements of leaf absorption values (µg/m2) recorded at 0, 10, and 30 meters from the roadside source, along with the overall daily averages and incremental daily absorption changes. These data illustrate the temporal accumulation rate of dust particulates on dominant tree species within the urban forest buffer zone.

| Date | Daily absorption value (µg/m²) | | | Average (µg/m²) | Difference in value absorption per day (µg/m²) |
|---|---|---|---|---|---|
| | 0 meters | 10 meters | 30 meters | | |
| 29 April 2025 | 137,945.01 | 97,648.25 | 70,642.84 | 102,078.70 | - |
| 6 May 2025 | 185,775.56 | 94,127.07 | 73,304.95 | 117,735.86 | 15,657.16 |
| 13 May 2025 | 192,021.49 | 101,853.58 | 97,514.41 | 130,463.16 | 12,727.30 |
| Average | 171,914.02 | 97,876.30 | 80,487.40 | 116,759.24 | 14,192.23 |

The particle absorption values on leaves increased from the first week to the third week, with a daily average of 14,192.23 µg/m². Although the weekly absorption values increased, the average absorption based on distance decreased, especially from 0 m to 10 m, with a decrease of 43.07%. This shows the ability of vegetation to reduce dust particles from roads. Trees with dense canopies, rough-textured trunks and branches, and high canopy density are more effective in capturing dust particles [24,25]. The increase in absorption values each week was due to the accumulation of dust from various sources, such as roads, vehicles, and industries. In addition, the position and location of the canopy on the green belt affect the amount of dust absorption [26].

***Equivalence of Low Volume Water Sampler and Digital Tools***

To ensure the accuracy of the $PM_{2.5}$ and $PM_{10}$ digital sensor readings, the instruments were first calibrated using a Low Volume Air Sampler (LVAS). Dramaga Highway was specifically chosen as the calibration site because its traffic volume is similar to that of the study area. This process was conducted over five sampling sessions from morning to afternoon (8:00 AM–5:00 PM). Subsequently, conversion factors were derived by comparing the digital device's response to LVAS data that had been validated by PT Atmos Laboratorium Indonesia. Based on this comparison, the correction values obtained were 0.66 and 0.54 for $PM_{2.5}$ and 0.75 and 0.58 for $PM_{10}$, as summarized in Table 7.

**Table 7.** Calibration results and correction factor derivation for digital air quality sensors against the reference Low Volume Air Sampler (LVAS). The table displays comparative concentrations (µg/m³) of $PM_{2.5}$ and $PM_{10}$ recorded across five sampling sessions at Dramaga Highway using both standard LVAS and two digital measurement units. These experimental trials served to determine the empirical correction factors required to align digital sensor outputs with standard gravimetric reference values.

| Sample | LVAS Measurement Results (µg/m³) | Digital device measurement results 1 | Digital device measurement results 2 | Tool conversion 1 | Tool conversion 2 |
|---|---|---|---|---|---|
| $PM_{2.5}$ | | | | | |
| I | 10.53 | 24.14 | 29.14 | 0.44 | 0.36 |
| II | 10.99 | 16.00 | 20.71 | 0.69 | 0.53 |
| III | 9.26 | 13.71 | 16.71 | 0.68 | 0.55 |
| IV | 11.14 | 12.29 | 15.86 | 0.91 | 0.70 |
| V | 12.67 | 20.57 | 22.71 | 0.62 | 0.56 |
| Correction Factor | | | | 0.66 | 0.54 |
| $PM_{10}$ | | | | | |
| I | 15.85 | 30.71 | 38.00 | 0.52 | 0.42 |
| II | 11.96 | 19.71 | 26.71 | 0.61 | 0.45 |
| III | 15.04 | 17.43 | 22.57 | 0.86 | 0.67 |
| IV | 15.05 | 14.57 | 20.00 | 1.03 | 0.75 |
| V | 17.67 | 25.43 | 28.43 | 0.69 | 0.62 |
| Correction Factor | | | | 0.75 | 0.58 |

***Particulate Matter 2.5 μg/m³ ($PM_{2.5}$) concentration***

$PM_{2.5}$ concentrations were measured at PBB UF and Patriot Candrabhaga Stadium. These measured pollution levels were heavily influenced by the high traffic activity on Ahmad Yani Street. The surrounding area is known to be very congested with various motor vehicles throughout the day. Field data were collected at several designated research plots over a period of four days from Wednesday to Saturday. Finally, the team conducted three separate measurements per day, which were divided into morning, afternoon, and evening sessions. The measurement results are presented in Table 8.

**Table 8.** $PM_{2.5}$ concentration sampling results across vegetated and open plots based on the number of days and observation sessions. The table presents fine particulate matter concentrations (μg/m³) recorded across three observation sessions (morning, afternoon, and evening) over four sampling days (March 19–22, 2025) at gradient distances of 0, 10, and 30 meters. These data illustrate the comparative attenuation of $PM_{2.5}$ levels provided by the urban forest canopy compared to the unvegetated open plot area.

| Observation time | $PM_{2.5}$ Concentration (μg/m³) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Vegetation plot | | | | Open Plot | | | |
| | 0 m* | 10 m* | 30 m* | Average | 0 m* | 10 m* | 30 m* | Average |
| Wednesday, March 19, 2025 | | | | | | | | |
| 08:00–09:00 AM | 11.19 | 8.89 | 7.61 | 9.23 | 16.56 | 15.76 | 14.91 | 15.75 |
| 00:00–01:00 PM | 10.34 | 7.67 | 6.69 | 8.23 | 16.59 | 15.84 | 14.89 | 15.77 |
| 04:00–05:00 PM | 13.42 | 11.06 | 10.18 | 11.56 | 17.10 | 16.05 | 15.07 | 16.07 |
| Average | 11.65 | 9.21 | 8.16 | 9.67 | 16.75 | 15.88 | 14.96 | 15.86 |
| Thursday, March 20, 2025 | | | | | | | | |
| 08:00–09:00 AM | 16.50 | 14.02 | 12.35 | 14.29 | 20.06 | 19.31 | 18.15 | 19.17 |
| 00:00–01:00 PM | 13.92 | 11.57 | 10.40 | 11.96 | 16.69 | 16.25 | 15.35 | 16.10 |
| 04:00–05:00 PM | 9.18 | 8.36 | 7.67 | 8.40 | 11.85 | 11.16 | 10.26 | 11.09 |
| Average | 13.20 | 11.31 | 10.14 | 11.55 | 16.20 | 15.57 | 14.59 | 15.45 |
| Friday, March 21, 2025 | | | | | | | | |
| 08:00–09:00 AM | 12.89 | 10.43 | 9.52 | 10.95 | 16.02 | 15.40 | 14.30 | 15.24 |
| 00:00–01:00 PM | 12.32 | 11.03 | 9.59 | 10.98 | 15.33 | 14.66 | 13.71 | 14.56 |
| 04:00–05:00 PM | 15.24 | 10.62 | 8.61 | 11.49 | 18.36 | 17.90 | 16.84 | 17.70 |
| Average | 13.48 | 10.70 | 9.24 | 11.14 | 16.57 | 15.99 | 14.95 | 15.83 |
| Saturday, March 22, 2025 | | | | | | | | |
| 08:00–09:00 AM | 21.72 | 19.61 | 19.30 | 20.21 | 24.63 | 24.12 | 22.81 | 23.85 |
| 00:00–01:00 PM | 19.74 | 17.03 | 15.65 | 17.47 | 22.91 | 22.45 | 21.21 | 22.19 |
| 04:00–05:00 PM | 18.67 | 17.47 | 15.24 | 17.13 | 26.25 | 23.68 | 23.14 | 24.36 |
| Average | 20.04 | 18.04 | 16.73 | 18.27 | 24.60 | 23.42 | 22.39 | 23.47 |

* Distance from the edge of the urban forest closest to the road or located directly in front of the first tree trunk.

The average $PM_{2.5}$ concentration on weekdays in the vegetation plot was 12.78 μg/m³ at a distance of 0 m, 10.41 μg/m³ at a distance of 10 m, 9.18 μg/m³ at a distance of 30 m, and the average across all distances was 10.79 μg/m³. Government Regulation No. 22 of 2021 sets the 24-hour threshold for $PM_{2.5}$ at 55 μg/m³, with no standard for 1-hour duration. Data from Kayuringin, Bekasi showed an upward trend in $PM_{2.5}$ concentrations from 2022 to 2024, with a significant spike in 2024. 2022 had the lowest levels (25–45 μg/m³) and relatively good air quality, with a low point of approximately 20 μg/m³ in October (Figure 2).

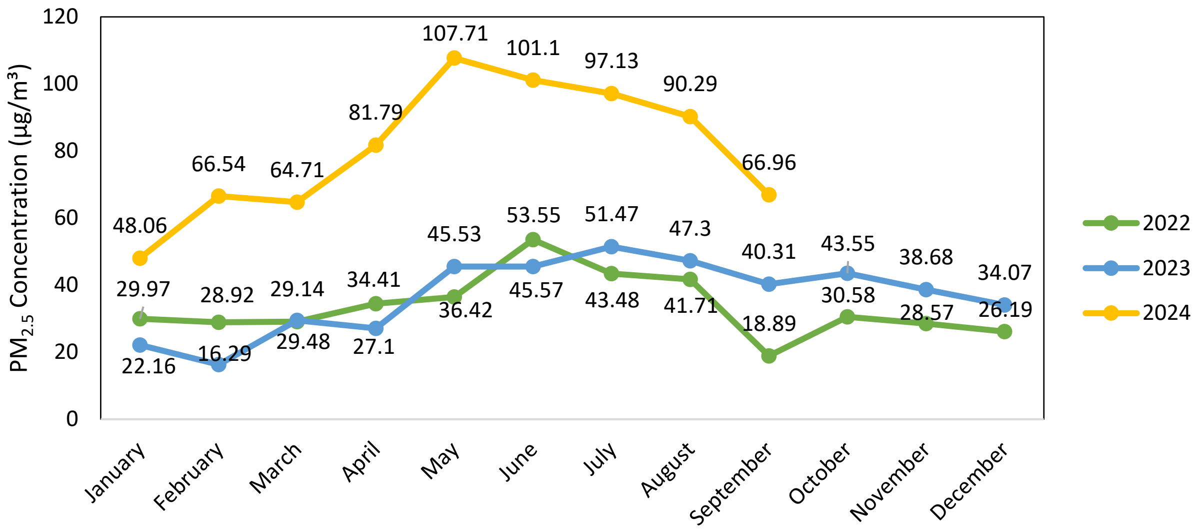


**Figure 2.** Monthly $PM_{2.5}$ concentration trends recorded by the Air Quality Monitoring System (AQMS) in Kayuringin Jaya. The line graph depicts the interannual and seasonal variations in monthly average $PM_{2.5}$ levels (µg/m³) across three consecutive years (2022, 2023, and 2024). The data illustrate a notable upward trajectory in fine particulate pollution over time, with prominent concentration peaks occurring during the mid-year dry season months (May–July).

In 2023, $PM_{2.5}$ concentrations in Kayuringin increased compared to 2022, ranging from 20 to 50 µg/m³ and peaking in June–July, although still below the threshold of 55 µg/m³ stipulated in Government Regulation No. 22 of 2021. The high level of fluctuations recorded confirms the dynamics of human activity and shifts in environmental conditions that directly impact air quality. For the record, a massive spike is expected in 2024. Since early January of that year, pollutant concentration levels had already exceeded the 50 µg/m³ threshold and continued to climb steadily, peaking at approximately 110 µg/m³ in May. Worse still, this trend remained high until the end of the year, without ever dropping below 65 µg/m³. The absence of a decline reflects poor air quality, as the levels continuously exceeded the safe threshold for public health. Fluctuations in pollutant levels aligned with seasonal changes, particularly during the dry season (May–August) and the transitional period leading up to the rainy season (October–December). This phenomenon is strongly suspected to be driven by a combination of high vehicle traffic, widespread open burning, and low rainfall, which hinders the natural breakdown of particulate matter.

The difference in $PM_{2.5}$ levels between vegetated green areas and open areas was found to be statistically significant. This is indicated by *Sig.* The value of 0.000 obtained from the independent samples t-test is well below the critical threshold of 0.05. Vegetation has been proven to be more effective in reducing $PM_{2.5}$ concentrations, with an average reduction of 24.16% in vegetation plots and 9.76% in open plots within 0–30 m of the emission source (Table 9). These results reinforce the role of vegetation in reducing air pollution, particularly fine particles such as $PM_{2.5}$. When compared to the results of Syahraeni's [8] study, the reduction effectiveness at PBB UF is higher because the vegetation on the green belt of the toll road only reduced $PM_{2.5}$ by 5.02% in the vegetation plot and 3.13% in the open plot.

**Table 9.** Reduction magnitude and effectiveness of average $PM_{2.5}$ concentrations across distance gradients. The table details the absolute concentration decrease (µg/m³), percentage reduction (%), and overall mitigation effectiveness (%) compared between the Vegetation Plot and Open Plot across distance intervals of 0–10 m and 0–30 m from the emission source. These results quantify the significant role of the urban forest canopy in attenuating fine particulate pollution relative to unvegetated open space.

| Distance (m) | Decrease in $PM_{2.5}$ Concentration | | | | Effectiveness (%) |
|---|---|---|---|---|---|
| | Vegetation plot (µg/m³) | % | Open plot (µg/m³) | % | |
| 0 | 14.59 | - | 18.53 | - | |
| 0–10 | 2.28 | 15.61 | 0.81 | 4.39 | 11.22 |
| 0–30 | 3.53 | 24.16 | 1.81 | 9.76 | 14.40 |

The effectiveness of PBB UF in reducing $PM_{2.5}$ concentrations at a distance of 30 m reached 14.40%, which is higher than the results of Syahraeni [8] study on the green belt of the toll road, which was only 1.89%. The dynamics of air mass movement are strongly suspected to be the primary factor driving these differences, particularly in the transportation of particulate pollutants to the study area. Based on an analysis of the wind rose diagram, the dominant wind patterns at both observation sites blew from the west, southwest, and northwest, which were directed straight toward the measurement points. This movement pattern optimizes the role of vegetation as a natural filter for $PM_{2.5}$, particularly when wind gusts support the mechanism for capturing these particles. In general, wind direction and speed play crucial roles in pollutant dispersion; the direction determines which areas are affected, whereas the speed dictates how far particulate matter can travel in the atmosphere [27].

***Particulate Matter 10 µg/m³ ($PM_{10}$) concentration***

To compare the impact of vegetation on particulate pollution, $PM_{10}$ concentrations were measured in the green areas of PBB UF and the open areas at the entrance of Candrabhaga Stadium. The primary source of pollution at these locations is strongly suspected to be vehicle exhaust from the passing traffic. Sample collection was scheduled over four days, from Wednesday to Saturday, with each day divided into morning, afternoon, and evening sessions. The detailed data from these observations are summarized in Table 10 below.

**Table 10.** $PM_{10}$ concentration sampling results across vegetated and open plots based on the number of days and observation sessions. The table presents coarse particulate matter concentrations (µg/m³) recorded across three daily observation sessions (morning, afternoon, and evening) over four sampling days (March 19–22, 2025) at distances of 0, 10, and 30 meters from the roadside. These data illustrate the comparative attenuation of $PM_{10}$ levels facilitated by the urban forest canopy relative to the open plot area.

| Observation time | $PM_{10}$ Concentration (µg/m³) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Vegetation plot | | | | Open Plot | | | |
| | 0 m* | 10 m* | 30 m* | Average | 0 m* | 10 m* | 30 m* | Average |
| Wednesday, 19 March 2025 | | | | | | | | |
| 08:00–09:00 AM | 18.82 | 13.46 | 10.50 | 14.26 | 21.79 | 20.69 | 19.50 | 20.66 |
| 00:00–01:00 PM | 14.29 | 10.39 | 9.14 | 11.27 | 18.17 | 17.48 | 16.38 | 17.34 |
| 04:00–05:00 PM | 20.29 | 15.68 | 14.25 | 16.74 | 23.72 | 22.73 | 21.93 | 22.79 |
| Average | 17.80 | 13.18 | 11.30 | 14.09 | 21.23 | 20.30 | 19.27 | 20.27 |
| Thursday, 20 March 2025 | | | | | | | | |
| 08:00–09.00 AM | 25.21 | 19.96 | 17.75 | 20.98 | 28.56 | 27.48 | 27.09 | 27.71 |
| 12:00–13:00 PM | 20.61 | 16.11 | 14.50 | 17.07 | 24.25 | 23.28 | 22.21 | 23.25 |
| 16:00–17:00 PM | 13.07 | 11.75 | 9.39 | 11.40 | 17.04 | 16.74 | 15.36 | 16.38 |
| Average | 19.63 | 15.94 | 13.88 | 16.48 | 23.28 | 22.50 | 21.55 | 22.45 |
| Friday, 21 March 2025 | | | | | | | | |
| 08:00–09:00 AM | 18.25 | 14.71 | 13.25 | 15.40 | 21.71 | 20.71 | 19.55 | 20.66 |
| 00:00–01:00 PM | 17.54 | 14.71 | 13.11 | 15.12 | 20.47 | 19.75 | 18.73 | 19.65 |
| 04:00–05:00 PM | 22.07 | 16.39 | 12.36 | 16.94 | 25.80 | 25.44 | 23.89 | 25.04 |
| Average | 19.29 | 15.27 | 12.90 | 15.82 | 22.66 | 21.97 | 20.72 | 21.78 |
| Saturday, 22 March 2025 | | | | | | | | |
| 08:00–09:00 AM | 32.14 | 29.39 | 27.29 | 29.61 | 34.47 | 33.42 | 32.18 | 33.35 |
| 00:00–01:00 PM | 29.54 | 25.04 | 22.57 | 25.71 | 32.92 | 32.40 | 31.51 | 32.28 |
| 04:00–05:00 PM | 27.11 | 24.32 | 21.54 | 24.32 | 30.57 | 29.88 | 28.70 | 29.72 |
| Average | 29.60 | 26.25 | 23.80 | 26.55 | 32.65 | 31.90 | 30.80 | 31.78 |

* Distance from the edge of the urban forest closest to the road or located directly in front of the first tree trunk.

The average $PM_{10}$ concentration on weekdays in the vegetation plot was 16.93 µg/m³ at 0 m, 15.81 µg/m³ at 10 m, and 14.83 µg/m³ at 30 m, and the average across all distances was 15.71 µg/m³. The ambient air quality standard for

PM$_{10}$ over a 24-hour period is set at 75 µg/m³, whereas the standard for a 1-hour duration is not yet available [28]. Based on data from the Kayuringin area, Bekasi City, during 2022–2024, the seasonal pattern of PM$_{10}$ concentrations showed a similar trend, namely, an increase in the middle of the year and a decrease towards the end of the year. In 2022, concentrations increased gradually from January to June, reaching a peak of approximately 75 µg/m ³, and then slowly decreased until December. The year 2023 showed a similar trend but with slightly higher concentration levels, especially from May to August, with the highest value of approximately 70 µg/m³, indicating an increase in pollution compared to the previous year. Meanwhile, 2024 showed relatively lower PM$_{10}$ concentrations throughout the year, indicating an improvement in air quality compared with the previous two years (Figure 3).

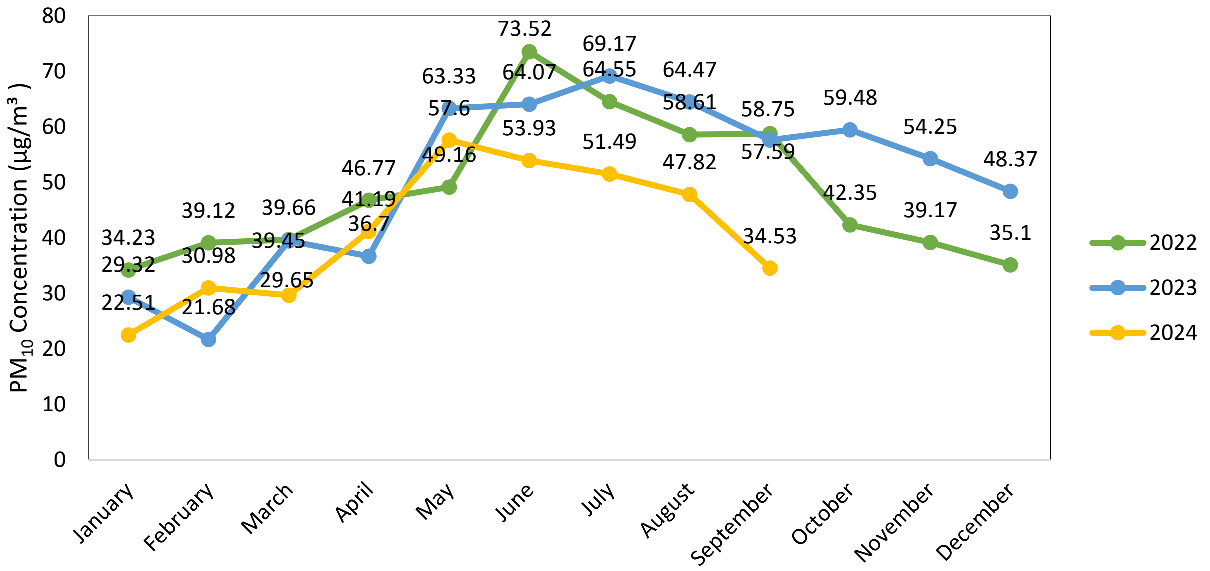


**Figure 3.** Monthly PM10 concentration trends recorded by the Air Quality Monitoring System (AQMS) in Kayuringin Jaya. The line graph depicts the interannual and seasonal variations in monthly average PM10 levels (µg/m³) across three consecutive years (2022, 2023, and 2024). The data illustrate a notable upward trajectory in fine particulate pollution over time, with prominent concentration peaks occurring during the mid-year dry season months (May–July).

PM$_{10}$ concentrations in 2024 began to increase in May but remained lower than those in 2022 and 2023 and then declined sharply in August–September, indicating an improvement in air quality. This pattern shows that mid-year had the highest concentrations due to the dry season and increased vehicle or industrial activity, while the decline at the end of the year was influenced by rainfall and reduced pollution sources. Unlike PM$_{2.5}$, the air quality based on PM$_{10}$ in 2024 was better. The results of the Independent Sample T-test show a significant difference (Sig. 0.000 < 0.05) between vegetated and open areas, where vegetation has been proven to effectively reduced PM$_{10}$ concentrations. Further analysis measured the effectiveness of green belts in reducing PM$_{10}$ at distances of 10 and 30 m from emission sources (Table 11).

**Table 11.** Reduction magnitude and effectiveness of average PM$_{10}$ concentrations across distance gradients. The table details the absolute concentration decrease (µg/m³), percentage reduction (%), and overall mitigation effectiveness (%) compared between the Vegetation Plot and Open Plot across distance intervals of 0–10 m and 0–30 m from the emission source. These results quantify the significant role of the urban forest canopy in attenuating fine particulate pollution relative to unvegetated open space.

| Distance (m) | Decrease in PM10 Concentration | | | | Effectiveness (%) |
|---|---|---|---|---|---|
| | Vegetation plot (µg/m3) | % | Open plot (µg/m3) | % | |
| 0 | 21.58 | - | 24.96 | - | |
| 0–10 | 3.92 | 18.15 | 0.79 | 3.16 | 14.99 |
| 0–30 | 6.11 | 28.30 | 1.87 | 7.50 | 20.81 |

The decrease in $PM_{10}$ concentration in vegetated areas was higher than that in open areas, namely 28.30% versus 7.50% within 0–30 m from the emission source. The effectiveness of urban forests in reducing $PM_{10}$ reached 20.81%, which was much greater than that of highway green belts, according to Syahraeni [8], which was only 1.37%. This difference is believed to be closely related to the direction of wind flow toward the study site, which in turn helps vegetation absorb pollutants more effectively. These findings indicate that trees and dense canopies play a major role in reducing PM10. This reduction occurs because the particles adhere to and settle on the surfaces of leaves and tree branches.

***Estimation of total particle absorption in PBB UF***

These direct observation data provide projection figures that are highly useful for the continuity of research. The precision of these data revealed the total amount of particulate pollutants that could be filtered by the PBB UF green space. For details on the figures and their classifications, all the calculation results are neatly organized in Table 12.

**Table 12** Scaling analysis of forest canopy capacity and daily particulate emission absorption in PBB UF. The dataset details the geometric properties of the urban forest stand, individual and stand-level daily dust absorption values, and corresponding daily vehicle emission loads. These figures summarize the overall ecological buffering capacity of the green space in mitigating local particulate air pollution.

| Parameters | Quantity | | Unit |
|---|---|---|---|
| Urban forest area | 3 ha | 30,000 | m2 |
| Planting distance | 6m x 6m | 36 | m2 |
| Crown diameter | 6 | | m |
| Length of vegetation strip | 300 | | m |
| Amount of vegetation within a 30 m depth path | 250 | | trees |
| Crown surface area per tree | 113.04 | | m2 |
| Daily pollutant absorption | 14,192.23 | | µg/m2 |
| Pollutant absorption per tree canopy per day | 1,604,289.68 | | µg |
| Daily absorption of urban forest pollutants | 401,072,419.80 | | µg |
| Daily absorption of urban forest pollutants | 401.07 | | g |
| Average emissions/hour/km | 479.64 | | g/km/vehicle |
| Emissions/hour | 143.89 | | g/vehicle |
| Daytime emissions | 1,726.70 | | g |
| nighttime emissions | 1,726.70 | 518.01 | g |
| Daily emissions | 2,244.72 | | g |
| Percentage of emissions absorbed | 17.87 | | % |

The area of the observed urban forest was approximately 3 ha, equivalent to 30,000 square meters. Mahogany trees were assumed to have a planting distance of 6 m × 6 m, with an average tree crown diameter of 6 m. The vegetation line was approximately 300 m long, with approximately 50 trees in the vegetation line. Overall, the amount of vegetation in the observation path reached 250 trees, with an average crown surface area per tree of 113.04 m². The daily particle absorption capacity of the leaf surfaces was recorded as 14,192.23 µg/m². Calculated per tree canopy, the particle absorption capacity reached 1,604,289.68 µg per tree per day. The daily accumulation of absorption by the entire urban forest was 401,072,419.80 µg, equivalent to 401.07 g.

The estimated average vehicle emissions in the area were 479.64 g/km/vehicle, with an average hourly emission rate of 143.892 g/vehicle. The total vehicle emissions during the day were estimated to be 1,726.70 g, and assuming that the number of vehicles at night was 30% of the number of vehicles during the day, the estimated vehicle emissions at night were 518.01 g. The total daily vehicle emissions were 2,244.72 g. Thus, the ability of urban forests to absorb pollutants is only approximately 17.87% of the total daily vehicle emissions, indicating a relatively small contribution to reducing pollution concentrations in the area. This value was obtained from the assumption that all trees were mahogany with the same crown shape and strata.

## Discussion

### *Analysis of changes in $PM_{2.5}$ and $PM_{10}$ concentrations based on observed variables*

Linear regression tests were conducted to determine the extent to which several factors influence air quality. The analyzed factors included the distance from the emission source, wind speed, wind direction, and estimated vehicle emissions. Additionally, the statistical test examined the LAI values and absorption capacity of the leaves. This analysis measured the direct impact of these variables on changes in $PM_{2.5}$ and $PM_{10}$ concentrations in vegetated and open areas. Ultimately, this test helps to understand how each specific variable contributes to air pollution levels at the study site.

### *Distance from the emission source*

The further away from the highway, the lower the concentration of $PM_{2.5}$ and $PM_{10}$, with a negative correlation. A significant decrease was observed in the vegetated areas ($p < 0.05$) but not in the open areas. Distance contributed little to the decrease in PM concentrations (11.81 % (PM2.5) and 15.10 % (PM10) in vegetated areas). This is in line with the findings of Popek et al. [29], which states that the amount of PM accumulated on *Tilia cordata* Mill. The PM concentration in leaves depends on the distance from the source of PM emissions, with significantly higher concentrations found on trees growing closer to the source of emissions. The weak relationship in open areas is likely influenced by the daily fluctuations in pollutants. The ability of urban trees to capture PM is a form of phytoremediation. With strategic planning, this natural process can be harnessed to design PBB UF that functions as a haven of better air quality in urban environments.

### *Wind speed and direction*

A positive relationship was found between wind speed and PM concentration, indicating that the higher the wind speed, the higher the $PM_{2.5}$ and $PM_{10}$. This is due to particle resuspension and the long-distance transport. A significant relationship was only found in vegetated areas ($p < 0.05$), with a contribution of 15.29% ($PM_{2.5}$) and 18.82% ($PM_{10}$), while in open areas, the effect was very small. Elevated wind speeds are conducive to lifting dust from the ground, which in turn increases the concentration of coarse particles [30]. In this study, the dominant wind conditions were downwind, indicating that the wind direction had the potential to carry pollutants from emission sources toward the vegetation plots. Downwind conditions were observed during all observation sessions at both sites.

### *Estimated vehicle emission*

This factor showed the most dominant influence, with a very strong correlation with PM increases. The $R^2$ value reached 89.78% ($PM_{2.5}$) and 87.36% ($PM_{10}$) in vegetated areas, and 75.61% and 81.78% in open areas. The amount of pollutants emitted by diesel vehicles actually depends heavily on two factors: road conditions and the emission standards in place [31]. Although strict emissions regulations have successfully reduced most gaseous pollutants, $NO_x$ emissions have actually shown the opposite trend. Meanwhile, from an operational standpoint, idling (the engine running without the vehicle moving) is the leading contributor to pollution for nearly all vehicle categories, whether diesel or gas-powered. However, $NO_x$ emissions from heavy-duty vehicles (HDVs) are once again an exception to this rule. This conclusion aligns with research [32], based on Sentinel-5P satellite imagery, which documented a decrease in air pollutants during the COVID-19 restrictions. The Large-Scale Social Restrictions (PSBB) policy in the Jakarta metropolitan area, which limited residents' movement and vehicle traffic, was the primary driver of this decline. This clearly demonstrates the significant impact of human transportation activities on air pollution levels. On the other hand, the data also highlights the crucial role of vegetation; plants were still able to reduce PM concentrations in the early stages even as vehicle emissions were at their peak.

### *Leaf Area Index (LAI) values*

The negative correlation between LAI values and PM concentrations indicates that tree canopy density is inversely proportional to $PM_{2.5}$ and $PM_{10}$ concentrations. Statistical data show that this relationship is significant ($p < 0.05$), with explanatory power of 12.01% for $PM_{2.5}$ and 15.22% for $PM_{10}$. Through its dense canopy, the PBB UF area is able to consistently absorb particulate pollutants at various points. The effectiveness of plants in filtering the air relies on the ability of leaf surfaces to trap fine particles. Therefore, forested areas with a high LAI are considered the most reliable type of vegetation for reducing air pollution [33]. The architecture of a tree canopy can create turbulence or air vortices in its vicinity. This phenomenon directly accelerates the deposition and absorption of $PM_{2.5}$ particles by leaf surfaces [34]. The effectiveness of this air filtration process is actually heavily influenced by the unique morphological characteristics of the leaves in each species. Microscopic factors such as the presence of trichomes (fine leaf hairs) and the epicuticular wax layer play a key role in optimizing the capture of these pollutants [35]. High LAI values in forest ecosystems often lead to a significant increase in total BVOC (Biogenic Volatile Organic Compounds) emissions. This phenomenon remains a critical consideration, although the specific characteristics and fluctuations in emission quality across different forest types still require further study. [36]. The forest canopy plays the most crucial role as the primary factor determining the effectiveness of forest ecosystems in reducing $PM_{2.5}$ [37]. This is because parameters such as canopy density and LAI are strongly correlated with fluctuations in $PM_{2.5}$ levels. In contrast, physical tree characteristics, such as diameter at breast height (DBH), do not appear to have a significant effect on the reduction of these pollutants.

***Leaf absorption capacity***

The mahogany species (*Swietenia macrophylla*) has been shown to possess an impressive particulate retention capacity, with an average daily absorption rate of 14,192.23 µg/m² and a trend of increasing accumulation each week. This high filtration efficiency is fully supported by a combination of leaf morphology, the presence of trichomes, and the macro-scale canopy density pattern. Through these structural advantages, this vegetation is effective in reducing PM pollution in the atmosphere. Thus, the integration of mahogany trees into urban green spaces can be relied upon as an effective nature-based solution for restoring urban air quality.

***Recommendations for tree vegetation management***

Although the tree species at PBB UF generally support the designation of the urban forest as a residential and recreational area, distribution imbalances still exist due to the excessive dominance of mahogany (Swietenia macrophylla). Vegetation restructuring measures must be implemented immediately, considering canopy density, leaf physical characteristics, and pollutant absorption capacity, to maximize ecological functions in filtering harmful particles ($PM_{10}$ and $PM_{2.5}$) in densely populated areas. Referring to Dahlan et al. [38] findings, leaves with trichome structures or fine hairs possess a comparative advantage in capturing particulate matter. This capture efficiency increases significantly if these trichomes (fine hairs) grow on both sides of the leaf, as their strategic position enables them to trap air pollutants and resume active filtration after their surfaces are washed by rainwater.

***Selection of species that efficiently absorb PM***

The selection of tree species should focus on species with leaf morphology that supports particle absorption, such as coarse, hairy (trichomes), waxy, and densely branched leaves. For roadside landscapes, it is necessary to consider the architectural form of the tree, the density of trichomes, and regional conditions. Dry areas and roads with heavy traffic require plants with a high ability to reduce pollution levels. According to Gandasari [39], the recommended species include *Cassia javanica* and *Sindora velutina*. Meanwhile, Ministry of Public Works and Housing of the Republic of Indonesia [40] listed various vegetation types that are effective air pollutant reducers (Table 13).

**Table 13.** Synthesis of recommended plant species for particulate matter mitigation based on literature review. The dataset presents candidate tree species suitable for green belt development, compiled from referenced literature source guidelines. These species are characterized by high pollutant capture capabilities, making them suitable choices for ecological restructuring in urban roadside environments.

| No | Scientific name | Common name | Source |
|---|---|---|---|
| 1 | *Cassia javanica* | Java Cassia | [39] |
| 2 | *Sindora velutina* | Silky hairy | [39] |
| 3 | *Pterocarpus indicus* | Amboyna wood | [40] |
| 4 | *Pitchecolobium dulce* | Manila tamarind | [40] |
| 5 | *Bambusa sp.* | Arrow bamboo | [40] |
| 6 | *Amherstia nobilis* | Pride of Burma | [40] |
| 7 | *Agathis alba* | White Damar | [40] |
| 8 | *Elaeocarpus grandisflora* | Fairy petticoats | [40] |
| 9 | *Polyathea sp.* | Pond-shaped tree | [40] |
| 10 | *Polyathea longifolia* | Mast Tree | [40] |
| 11 | *Caesalphinia pulcherima* | Peacock Flower | [40] |
| 12 | *Hibiscusrosa sinensis* | Chinese hibiscus | [40] |
| 13 | *Canarium commune* | Java almond | [40] |
| 14 | *Terminalia cattapa* | Tropical almond | [40] |

| No | Scientific name | Common name | Source |
|---|---|---|---|
| 15 | *Spathodea companulata* | African tulip tree | [40] |
| 16 | *Filicium decipiens* | Ferntree | [40] |
| 17 | *Bauhinia purpurea* | Butterfly tree | [40] |
| 18 | *Lantana camara* | Common Lantana | [40] |
| 19 | *Switenia mahagoni* | West Indian mahogany | [40] |
| 20 | *Musaenda sp* | Ashanti blood | [40] |
| 21 | *Nerium oleander* | Oleander | [40] |
| 22 | *Eugenia polyantha* | Indonesian bay-leaf | [40] |
| 23 | *Sanseviera trifasciata L* | Snake Plant | [40] |
| 24 | *Acalypha* sp. | Wild tea | [40] |

Several tree species have a high capacity to absorb dust particles (PM) and are adaptable to tropical urban climatic conditions and resistant to pollutants. According to Rahmadhani et al. [41], the Tanjung tree (*Mimusops elengi*) is effective at absorbing dust because its leaves have a smooth surface, wavy edges, curve upward, and have dense veins that make it easy for dust to stick to them. The selection of trees for road medians must consider not only physical characteristics but also the safety and comfort of road users. Hakim [42] emphasized that the criteria for trees that are most effective at reducing dust pollution are based on three key factors: dense canopy, high vegetation resilience, and ability to shed leaves periodically. This leaf regeneration cycle is crucial for ensuring that the surfaces of newly formed young leaves remain in optimal condition to capture dust particles as effectively as possible. Azzahro et al. [24] expanded this list of potential vegetation by recommending several types of urban trees, such as kersen (*Muntingia calabura*), trembesi (*Samanea saman*), tanjung (*Mimusops elengi*), and ketapang (*Terminalia catappa*). The advantages of these species lie in the heterogeneity of their leaf morphology, whether rough-textured, lobed, or needle-shaped, combined with a high trichome density and dense canopies. This combination of structural features makes them highly ideal for reducing the burden of particulate pollutants in urban areas.

***Vertical and horizontal grouping of vegetation***

Air pollutant filtration can be optimized through vertical and horizontal green space planning approaches (Figure 4). In the vertical dimension, vegetation zoning is developed based on canopy stratification [43], which divides the spatial structure into three synergistic levels to maximize the interception of exhaust gas. The basal stratum, inhabited by vegetation groups under 5 m in height, prioritizes dense-leaved shrubs or short trees with rough surfaces or trichomes. These physical characteristics are highly effective for trapping large particulates floating near the ground surface. Moving to the middle stratum (height range 5–15 m), planting focuses on medium-sized trees with wide, dense canopies to settle both fine and coarse particles. Leaves with rough, waxy, and flat characteristics are highly recommended in this layer to enhance pollutant deposition efficiency. Meanwhile, the upper stratum, populated by tall trees exceeding 15 m, serves a dual purpose: in addition to acting as a barrier against high-speed wind currents, this upper canopy actively filters fine particulate matter, such as $PM_{2.5}$, carried in from surrounding areas. This inter-stratum collaboration forms a multilayer filtration system that significantly boosts the capacity of urban green spaces to improve air quality.

Horizontally, the structural configuration of the tree stands is arranged to follow the pattern of the local prevailing wind direction. The design of this green belt is based on the orientation and location of the primary sources of pollution. Using this approach, tree species with dense canopies are placed on the front line, directly bordering heavily trafficked highway corridors. This row of trees serves as a mechanical buffer zone that both breaks and isolates the flow of contaminated air. This strategic interception accelerates the deposition of particulate matter in the buffer zone, thereby mitigating the spread of pollutants before they reach public areas or recreational spaces within urban forests.


**Figure 4.** Schematic cross-section of the recommended multi-layered vegetation buffer for the Bekasi City PBB UF corridor. The diagram details the spatial allocation and planting arrangement of trees and shrubs relative to traffic lanes and walkways across specified distance intervals. This strategic canopy architecture establishes a green barrier to reduce wind velocity and optimize foliage surface area for capturing vehicle-derived air pollutants.

***Planting density and canopy pattern***

The planting distance of trees in urban forests must be adjusted according to the type of tree, canopy size, and environmental conditions to effectively reduce air pollution. Generally, the planting distance for medium-sized trees is 3–5 m, whereas for large trees, it is 5–8 m. Based on the Ministerial Regulation [40], plants along road corridors function as windbreaks to reduce the impact of strong winds on vehicles. The integration of tall-canopied trees and dense shrub groups is ideally implemented through row or cluster patterns with close planting distances, that is, less than 3 m. This vegetation density is intentionally designed so that the canopies of the trees overlap (interlocking canopy), thereby forming a solid, green corridor. Such a corridor structure plays a crucial role in reducing wind speed while optimizing the leaf surface area to trap and absorb particulate pollutants.

***Care and monitoring***

The maintenance of urban forest vegetation must be carried out sustainably to ensure that the ability of trees to absorb particles remains optimal. The continued ecological function of urban trees depends heavily on the effectiveness of the implemented silvicultural measures. Pruning dry or overgrown branches is a top priority for improving light penetration and air circulation within the canopy. Furthermore, soil moisture is maintained through scheduled watering during the dry season, accompanied by a fertilization program as the primary source of nutrients for plants. Uniquely, physical interventions, such as washing or cleaning thick layers of dust from the foliage, play a crucial role in restoring leaf pores clogged by pollutants.

However, the aspect of monitoring vegetation performance must not be overlooked. Periodic monitoring must include diagnosing plant disease symptoms, mapping the physical growth rate of trees, and calculating air filtration efficiency by comparing the particulate density around the site. To supplement the data, macro-climatological conditions such as daily rainfall and urban air quality indices need to be documented, given that these two external factors are the primary triggers influencing tree metabolism in the filtering of pollutants.

## Conclusions

The Patriot Bina Bangsa Urban Forest (PBB UF) has been shown to make a tangible contribution to improving air quality along the highway corridor, as evidenced by its ability to reduce $PM_{2.5}$ concentrations by 14.40% and $PM_{10}$ concentrations by 20.81%, respectively. At the vegetation level, mahogany leaves possessed an impressive dust retention capacity, reaching 14,192.23 μg/m² per week, although this filtration efficiency showed a declining trend as the distance from the emission source increased. Data analysis confirmed that tree placement and canopy density are the primary factors influencing absorption performance. Although this green space intervention is crucial for mitigating urban air pollution, the emission load from vehicle exhaust remains the most dominant contributor to PM fluctuations in the field. The scope of this study focused on the PBBUF area, limiting observations to the variables of distance, estimated vehicle emission volume, Leaf Area Index (LAI), and local wind direction and speed dynamics. As a development step, further research in the PBBUF area is recommended to evaluate the pollutant absorption capacity across the full diversity of plant species present—not limited to mahogany alone—and to design a more even distribution of tree species. Comprehensive studies should also incorporate topography and non-vehicular pollution sources to achieve a complete understanding of pollutant spread.

## Author Contributions

**RRH**: Methodology, Software, Investigation, Writing - Review & Editing; **RH**: Conceptualization, Review – Supervision; **NN**: Conceptualization, Methodology, Analysis, Review

## AI Writing Statement

The authors did not use any artificial intelligence-assisted technologies in the writing process.

## Conflicts of interest

There are no conflicts to declare.


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