

Published online on the journal's web page: http://jurnal.usahid.ac.id/index.php/jamr

eISSN: 2797-2917

Journal of Applied Management Research

Wind Pattern Analysis for Vehicular Pollution Dispersion Using WRPLOT View: A Case Study of Tegar Beriman Road, Bogor Regency

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ARTICLE INFO

Received: 12 December 2025
Revised: 27 April 2026
Accepted: 10 May 2026

Keywords:

Wind Pattern, Wind Rose, Vehicular Emissions, Air Pollution Dispersion, WRPlot View

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ABSTRACT

The rapid growth of motor vehicles in urban areas significantly contributes to air pollution, particularly along high-traffic corridors such as Tegar Beriman Road, Bogor Regency. This study analyzes wind patterns and their influence on the dispersion of vehicular pollutants using WRPlot View 8.0, based on one-year meteorological data from BMKG. A descriptive quantitative approach was applied to process wind direction and speed data into wind rose diagrams and frequency distributions. Results show that wind direction is dominated by the northwest (NW) sector (48.22%), followed by the north (20.27%) and west (15.07%) sectors. Wind speeds are mainly in the 3–4 m/s (46.30%) and 4–9 m/s (31.51%) ranges, indicating that over 77% of conditions fall within the moderate to strong categories. This reflects a dynamic atmospheric system with high dispersion capacity. The alignment between the dominant direction and wind speed suggests that pollutant transport is concentrated along a consistent pathway. As a result, emissions are likely dispersed toward the southeast (SE), with the primary downwind area potentially experiencing higher exposure. Although low wind speeds (21.92%) may allow localized accumulation, the absence of calm conditions indicates continuous airflow. These findings highlight the importance of wind patterns in shaping the distribution of urban air pollution and support the development of targeted, evidence-based air quality management strategies.

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1. INTRODUCTION

The growth in motor vehicle numbers in urban areas is a major contributor to rising air pollution, particularly in developing regions such as Bogor Regency, which is experiencing significant expansion in economic activity and human mobility (Zhang et al., 2021). The increase in traffic volume directly leads to higher emissions of exhaust gases containing various harmful pollutants, including fine particulate matter ($PM_{2.5}$ and PM_{10}), carbon monoxide (CO), nitrogen oxides (NOx), and hydrocarbons (HC), all of which are known to have serious impacts on human health and environmental quality (World Health Organization, 2021; Sukamdani & Sukwika, 2025). Long-term exposure to these pollutants has been associated with increased risks of respiratory diseases, cardiovascular disorders, and a decline in overall urban quality of life (Chen et al., 2020).

Tegar Beriman Road, as one of the main corridors in Bogor Regency, serves as a strategic center of governmental, commercial, and mobility activities, resulting in high traffic density (Kumar et al., 2022). This condition makes the area a significant source of air pollution emissions from the transportation sector. However, the level of air pollution in a given area is determined not only by emission magnitude but also by complex meteorological factors, particularly wind patterns (Seinfeld & Pandis, 2020). Therefore, air quality analysis cannot be separated from an understanding of atmospheric dynamics that control pollutant movement and distribution.

DOI: http://dx.doi.org/10.36441/jamr

Wind is a key factor in the transport and dispersion of pollutants in the atmosphere, where wind direction determines pollutant pathways, while wind speed influences the rate of dispersion, dilution, or accumulation of pollutants in a given area (Arya, 2021). Low wind speeds tend to cause pollutant accumulation near emission sources, whereas higher wind speeds enhance dispersion, allowing pollutants to spread over wider areas (Gulia et al., 2020). Thus, wind pattern characteristics play a crucial role in determining the spatial distribution of air pollution, particularly in urban areas where vehicular emissions are dominant.

Bogor Regency has meteorological characteristics influenced by complex topography, including mountainous regions and significant elevation variations, resulting in dynamic wind patterns both temporally and spatially (Prasetyo et al., 2022). This variability leads to uneven pollutant distribution in the atmosphere and strongly depends on local meteorological conditions at a given time (Putra et al., 2021). Therefore, the use of long-term meteorological data is essential to understand dominant wind patterns and pollutant dispersion tendencies more comprehensively (Wang et al., 2022).

Meteorological data obtained from the Meteorology, Climatology, and Geophysics Agency (BMKG) is a credible source widely used in environmental research for systematic analysis of atmospheric characteristics (BMKG, 2023). The use of annual data allows for the identification of more representative wind patterns, providing a more accurate picture of airflow dynamics over a specific period. Such analysis forms an important basis for understanding potential pollutant dispersion pathways in a given area.

One commonly used method for analyzing wind patterns is the wind rose visualization, which simultaneously illustrates the frequency distribution of wind direction and speed in an informative diagram (Goyal et al., 2021). This diagram enables the identification of dominant wind directions and speed characteristics that influence pollutant dispersion (Barman et al., 2020). In practice, WRPlot View version 8.0 is widely used in meteorological analysis for its ability to convert wind data into easily interpretable visualizations (Futari & Ali, 2023). This approach not only provides information on wind patterns but also serves as a basis for identifying potential directions of pollutant dispersion in urban environments (Rahman et al., 2022).

Previous studies have shown that integrating meteorological analysis with air quality studies can provide a deeper understanding of pollutant dispersion dynamics (Zhao et al., 2021). However, most of these studies focus on large-scale pollution sources such as industries, while research specifically addressing vehicular emissions at the urban road corridor scale remains limited (Singh et al., 2022). Additionally, many studies use short-term datasets, which may not adequately represent long-term wind patterns (Liu et al., 2020).

In Indonesia, particularly in Bogor Regency, studies examining wind patterns and potential dispersion directions of vehicular pollution using meteorological data remain limited, especially those employing wind rose visualization with WRPlot View (Hidayat et al., 2023). In fact, information on the dominant directions of pollution dispersion is crucial for supporting spatial planning, traffic management, and air quality control policies (Nasution et al., 2021). Without an adequate understanding of pollutant dispersion patterns, air pollution control strategies tend to be general and less effective in targeting the most affected areas (Kusuma et al., 2022).

Based on this background, this study aims to analyze wind pattern characteristics and identify potential dispersion directions of vehicular pollution along Tegar Beriman Road, Bogor Regency, using WRPlot View version 8.0 and one-year BMKG meteorological data. This study does not directly measure pollutant concentrations but employs a meteorology-based approach as a proxy to understand pollutant dispersion dynamics in the atmosphere. Therefore, the results are expected to provide an initial overview of air pollution dispersion patterns and serve as a basis for further comprehensive studies.

In addition to contributing to the scientific field of environmental meteorological analysis, this study is expected to support more effective, evidence-based environmental policymaking, particularly in urban air quality management (Zhao et al., 2021). By understanding wind patterns and potential pollutant dispersion pathways, local governments can identify priority areas for air pollution control and develop more targeted and sustainable mitigation strategies (Rahman et al., 2022).

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2. RESEARCH METHOD

This study employs a descriptive-analytical quantitative approach to analyze wind pattern characteristics and identify potential dispersion pathways of vehicular pollution along Tegar Beriman Road, Bogor Regency. The approach is appropriate because meteorological-based analysis, particularly wind direction and speed, is commonly used in preliminary atmospheric dispersion studies when direct pollutant concentration data are unavailable.

The data used consist of secondary meteorological data obtained from BMKG over a one-year period (January–December). The parameters analyzed include wind direction (degrees) and wind speed (m/s) with daily or hourly temporal resolution. The use of annual data aims to capture representative wind patterns and minimize seasonal bias.

Data preprocessing includes data cleaning, removal of missing values, and standardization of data formats to ensure compatibility with WRPlot View version 8.0. This step is crucial to ensure the accuracy and reliability of the analysis results. The data were processed using WRPlot View version 8.0 to generate wind rose visualizations representing the frequency distribution of wind direction and wind speed. Wind direction was classified into eight compass sectors: North (N), Northeast (NE), East (E), Southeast (SE), South (S), Southwest (SW), West (W), and Northwest (NW). Wind speed was categorized into four intervals: 0–3 m/s, 3–4 m/s, 4–9 m/s, and ≥9 m/s. This classification was applied to facilitate the interpretation of wind distribution patterns and to identify dominant wind directions and speed characteristics at the study site.

Data analysis was conducted by interpreting wind rose outputs and wind speed distributions to identify dominant directions, frequency of occurrence, and wind speed variations. The dominant wind direction was determined from the highest-frequency sector, while wind speed characteristics were analyzed using percentage distributions across speed classes.

Pollutant dispersion potential was interpreted conceptually using atmospheric dispersion principles, in which wind direction determines pollutant transport pathways, and wind speed influences dilution, spread, or accumulation. Downwind areas from emission sources were identified as zones with higher potential for pollution exposure.

3. RESULTS AND DISCUSSIONS

3.1. Result

Characteristics of Wind Patterns. The analysis of meteorological data obtained from the Meteorology, Climatology, and Geophysics Agency (BMKG) over a one-year period indicates that wind patterns in the Tegar Beriman Road area, Bogor Regency, exhibit relatively stable and well-defined characteristics (BMKG, 2023). This stability suggests that the local atmospheric system is not random but is influenced by geographical and topographical factors, including orographic effects from the surrounding mountainous regions (Prasetyo et al., 2022). In environmental meteorology, directional stability is a key indicator of pollutant transport and dispersion patterns in the atmosphere (Seinfeld & Pandis, 2020).

These characteristics indicate that airflow patterns in the study area have a dominant tendency that can be quantitatively identified, enabling further analysis of primary pollutant dispersion pathways. Moreover, the relatively dynamic atmospheric conditions without stagnation suggest continuous air mass movement throughout the observation period (Liu et al., 2020).

Wind Rose. Based on the wind rose visualization in Figure 1, wind patterns at the study site show a very strong dominance from the northwest (NW) sector. The frequency of wind from this sector is the highest among directions, indicating that air masses consistently originate from this sector throughout the observation period (Goyal et al., 2021).

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This dominance indicates that the wind pattern is not random but meteorologically structured and influenced by both regional and local conditions (Rahman et al., 2022). In the context of atmospheric dispersion, the prevailing wind direction serves as a key determinant of pollutant transport pathways from emission sources to surrounding areas (Arya, 2021).

The wind speed distribution in the wind rose shows a dominance of the 3.00–4.00 m/s and 4.00–9.00 m/s classes, which fall within moderate to relatively strong categories. These conditions reflect an active atmospheric dynamic that supports continuous pollutant dispersion (Futari & Ali, 2023). In contrast, low-wind-speed contributions are relatively small, and no calm conditions are observed, indicating that air movement occurs almost continuously without stagnation (Liu et al., 2020).

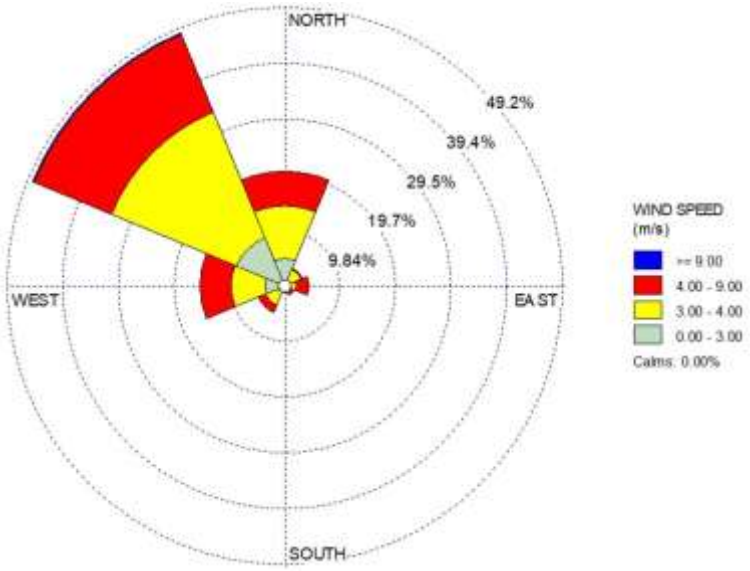
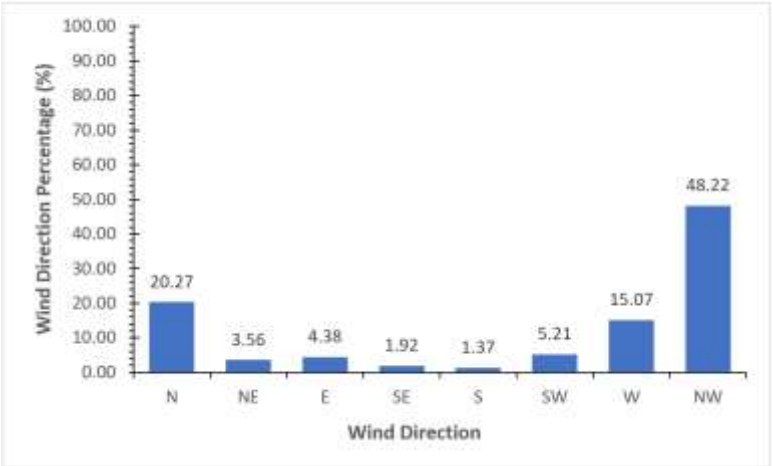


Fig 1. Wind Rose at Jalan Tegar Beriman, Bogor Regency
Source: Resulted by WRPLOT View (2026)

Wind Class Distribution Graph. Based on Figure 2. wind speed distribution is dominated by the 3.00–4.00 m/s class (46.3%), followed by 4.00–9.00 m/s (31.5%) and 0.00–3.00 m/s (21.9%) (BMKG, 2023). Very high wind speeds (≥9.00 m/s) are rare (0.3%), and no calm conditions were observed, indicating that the local atmosphere is relatively dynamic and supports continuous air mass movement (Wang et al., 2022; Liu et al., 2020). More than 77% of occurrences fall within moderate to relatively strong wind categories, suggesting conditions favorable for pollutant dispersion. This pattern reflects the general characteristics of tropical urban environments influenced by both local and regional factors (Gulia et al., 2020; Prasetyo et al., 2022).



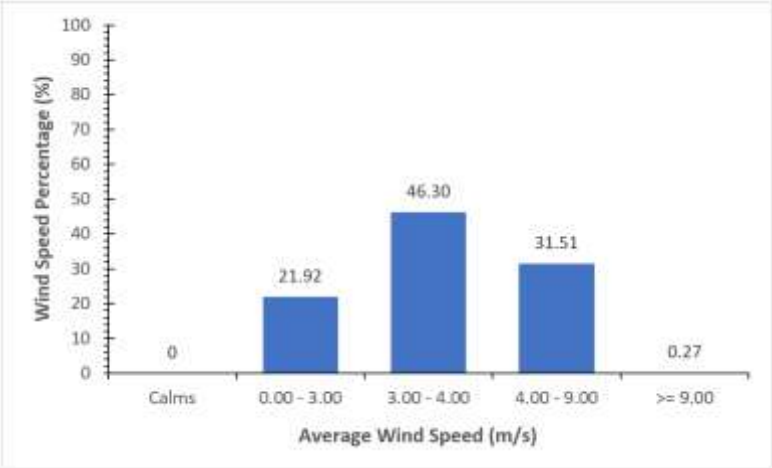
Source: Data Processed by WRPLOT View (2026)
Remarks: *North (N), Northeast (NE), East (E), Southeast (SE), South (S), Southwest (SW), West (W), and Northwest (NW)*

Fig 2. Distribution of Wind Direction Frequency on Jalan Tegar Beriman, Bogor Regency

DOI: http://dx.doi.org/10.36441/jamr

The wind direction distribution shows a strong dominance of the northwest (NW) sector (48.22%), followed by north (N) at 20.27% and west (W) at 15.07%. More than 80% of airflow is concentrated within the west–north quadrant (W–NW–N), indicating a strong and consistent directional pattern. Other directions (E, NE, SE, S, SW) each contribute less than 6%, suggesting a relatively minor role. The dominance of the northwest sector indicates that air masses predominantly move toward the opposite direction, namely the southeast (SE), which is likely to be the primary downwind area with higher potential for pollutant exposure.

Wind Speed Distribution. Based on Figure 3, the wind speed distribution is dominated by the 3.00–4.00 m/s class (46.30%), followed by 4.00–9.00 m/s (31.51%) and 0.00–3.00 m/s (21.92%). Very high wind speeds (≥9.00 m/s) are rare (0.27%), and no calm conditions were observed. Overall, more than 77% of occurrences fall within the moderate-to-relatively-strong wind categories, indicating a high capacity for atmospheric dispersion and continuous airflow dynamics (Gulia et al., 2020; Wang et al., 2022).



Source: Data Processed by WRPLOT View (2026)

Fig 3. Percentage Distribution of Wind Speed Classes on Jalan Tegar Beriman, Bogor Regency

The findings are reinforced by Table 1, which presents the joint distribution of wind direction and wind speed. Within the dominant speed class (3.00–4.00 m/s), the largest contribution comes from the northwest (NW) sector (23.84%), followed by the north (N) at 9.32% and the west (W) at 6.03%. A similar pattern is observed in the 4.00–9.00 m/s class, where the NW sector remains dominant (14.79%), followed by the N (6.03%) and W (5.48%) sectors. This indicates that wind speed dominance is strongly associated with the prevailing wind direction, namely the northwest sector.

Table 1. Joint Frequency Distribution of Wind Direction and Wind Speed Classes (%)

Directions / Wind Classes (m/s)	0.00 – 3.00	3.00 – 4.00	4.00 – 9.00	≥ 9.00	Total (%)
North (N)	4.93	9.32	6.03	0	20.27
Northeast (NE)	0.55	2.74	0.27	0	3.56
East (E)	0.55	1.64	2.19	0	4.38
Southeast (SE)	0.82	0	1.10	0	1.92
South (S)	0.82	0.27	0.27	0	1.37
Southwest (SW)	1.37	2.47	1.37	0	5.21
West (W)	3.56	6.03	5.48	0	15.07
Northwest (NW)	9.32	23.84	14.79	0.27	48.22
Sub-Total	**21.92**	**46.30**	**31.51**	**0.27**	**100**
Calms					0
Missing/Incomplete					0
Total					**100**

Source: Data Processed by WRPLOT View (2026)

In the low-wind-speed class (0.00–3.00 m/s), the directional distribution is more dispersed, although the NW sector still contributes the highest proportion (9.32%). Other sectors, such as NE, E, SE, and S, show relatively small contributions and no consistent dominant pattern, indicating higher directional variability under weak wind conditions.

DOI: http://dx.doi.org/10.36441/jamr

Very high wind speeds (≥9.00 m/s) are observed only in the NW sector, with a minimal contribution (0.27%), confirming that extreme conditions are rare and localized. Additionally, the absence of missing data and calm conditions indicates that the dataset is representative and captures continuous atmospheric conditions throughout the observation period.

Overall, the wind speed distribution—dominated by moderate-to-high categories and concentrated in the northwest sector—indicates a persistent, well-defined atmospheric flow pattern. An important implication of this pattern is that pollutant dispersion in the study area is not random but follows this dominant pathway, with potential transport toward the opposite (downwind) sector, namely the southeast (SE). Supported by sufficient wind speeds, pollutants are likely to be transported over longer distances and accumulate in primary receptor areas.

Summary of Results. Overall, the results indicate that wind patterns in the study area exhibit a clearly defined dominant direction (northwest), with wind speeds primarily in the moderate-to-high range. This combination suggests that the atmospheric system is both dynamic and directional, which strongly influences pollutant dispersion patterns (Seinfeld & Pandis, 2020). These findings provide an important basis for analyzing the relationship between wind patterns and the dispersion of vehicular pollution (Kumar et al., 2022).

3.2. Discussion

Influence of Wind Direction on the Spread of Pollution. The dominance of wind direction from the northwest (NW) sector indicates that pollutants generated by vehicular emissions along Tegar Beriman Road are predominantly transported toward the southeast (SE) as the primary downwind area. This is consistent with atmospheric dispersion principles, which state that wind direction determines pollutant transport pathways (Seinfeld & Pandis, 2020). This condition reflects a clear and consistent transport pathway in which pollutants are repeatedly advected toward specific sectors. As a result, pollutant distribution becomes spatially uneven, with downwind areas experiencing higher exposure levels compared to other regions (Kusuma et al., 2022).

Wind Direction Clustering Analysis (Quantitative Approach). To strengthen the analysis of dominant wind direction, a K-means directional clustering approach was applied. The results indicate that wind directions are grouped into two main clusters. The first cluster represents the dominant group, comprising the NW, N, and W sectors, with a combined contribution exceeding 80%, indicating a highly directional airflow pattern.

The second cluster comprises the remaining directions, which contribute relatively little and do not form a consistent pattern. This suggests that the atmospheric system in the study area is characterized by a single dominant airflow regime. The dominance of this cluster reinforces the presence of a consistent pollutant transport pathway toward the southeast sector, the primary downwind area.

Circular Statistics Analysis of Wind Direction. To further strengthen the quantitative analysis of wind direction, a circular statistics approach was employed to calculate the mean direction and circular variance. This approach is necessary because wind direction data are circular (0°–360°) and cannot be analyzed using conventional linear statistics (Seinfeld & Pandis, 2020).

Based on frequency-weighted calculations, the mean wind direction is approximately 312°, corresponding to the northwest (NW) sector. This indicates that, overall, the average wind direction at the study site consistently originates from the northwest. This result aligns with previous analyses showing NW dominance, thereby providing statistical validation of the descriptive and clustering findings.

The circular variance is approximately 0.32, indicating relatively low to moderate directional variability. This suggests that wind directions are not randomly distributed but are concentrated within a specific angular range. In meteorological terms, a relatively low circular variance indicates a stable and persistent airflow pattern in a dominant direction (Arya, 2021).

DOI: http://dx.doi.org/10.36441/jamr

The combination of a mean direction concentrated in the northwest sector and relatively low circular variance indicates a high degree of directional persistence, meaning that winds tend to move consistently in a primary direction. This condition significantly influences pollutant dispersion, as it implies that pollutant transport repeatedly follows the same pathway. Consequently, areas located opposite the mean direction—particularly the southeast (SE) sector—are likely to function as primary pollutant receptor zones (downwind accumulation areas). This directional consistency increases the potential for cumulative pollution exposure over time, especially when combined with wind speeds sufficient to transport pollutants over longer distances. Importantly, circular statistics analysis not only reinforces wind rose visualization and clustering results but also provides a more robust quantitative basis for identifying dominant airflow patterns and their implications for urban pollution dispersion (Rahman et al., 2022).

The circular statistical analysis reveals that the mean wind direction is approximately 312°, corresponding to the northwest (NW) sector, indicating a strong predominance of airflow from this direction. The circular variance value of 0.32 suggests relatively low to moderate directional variability, implying that wind directions are not widely dispersed but rather concentrated within a specific angular range (Table 2). This is further supported by the classification of the flow as persistent, indicating a stable and non-random wind pattern throughout the observation period. Such directional consistency plays a critical role in governing pollutant transport pathways, as it suggests that airborne pollutants are likely to be repeatedly advected toward the downwind sector, particularly the southeast (SE). Consequently, this statistical evidence strengthens the reliability of wind-based dispersion analysis and supports identifying spatially uneven pollution exposure in the study area.

Table 2. Results of Circular Statistics Analysis of Wind Direction at Tegar Beriman Road, Bogor Regency

Parameter	Value	Interpretation
Mean Direction	312° (NW)	Predominant wind direction
Circular Variance	0.32	Relatively low directional variability
Flow Characteristic	Persistent	Indicates a non-random directional pattern

Integration of Wind Patterns and Pollution Dispersion Dynamics. The spatial visualization in Figure 4 reinforces the previous analyses by illustrating the geographic distribution of pollutant dispersion under varying wind directions and speeds. The dominant dispersion pattern forms a sector extending from the emission source along Tegar Beriman Road toward the northwest (NW), as indicated by the widest areas shaded in red and yellow. The red (4–9 m/s) and yellow (3–4 m/s) zones dominate this pathway, suggesting that pollutant dispersion occurs not only consistently but is also sustained by wind speeds strong enough to transport pollutants over longer distances.

In contrast, low-wind-speed areas (0–3 m/s), shown in green, are relatively limited and concentrated near the emission source, indicating that pollutant accumulation is localized rather than dominant. This pattern confirms the presence of a stable, directional transport pathway in which air masses consistently carry pollutants toward specific sectors over time. Consequently, areas in the northwest sector of Tegar Beriman Road are likely to experience higher levels of air pollution exposure than other regions.

The integration of wind rose results, wind speed distribution, and spatial visualization indicates that the local atmospheric system is both directionally persistent and dynamically dispersive, meaning that pollutant dispersion patterns can be predicted with reasonable accuracy based on meteorological parameters (Rahman et al., 2022). This provides a strong basis for identifying priority areas in spatially based air pollution control.

The combination of dominant wind direction and wind speed distribution demonstrates that pollution dispersion patterns are both directional and dynamic. Wind direction determines the primary dispersion pathway, while wind speed governs the spatial extent of pollutant spread (Arya, 2021). These findings suggest that wind pattern analysis can serve as an initial approach for identifying potential pollutant dispersion pathways in urban areas. This approach is particularly relevant when direct pollutant concentration data are unavailable, as it provides spatial indications of the direction of dispersion (Rahman et al., 2022). In principle, wind rose analysis functions not only as a visualization tool but also as an analytical instrument to support environmental decision-making.

DOI: http://dx.doi.org/10.36441/jamr

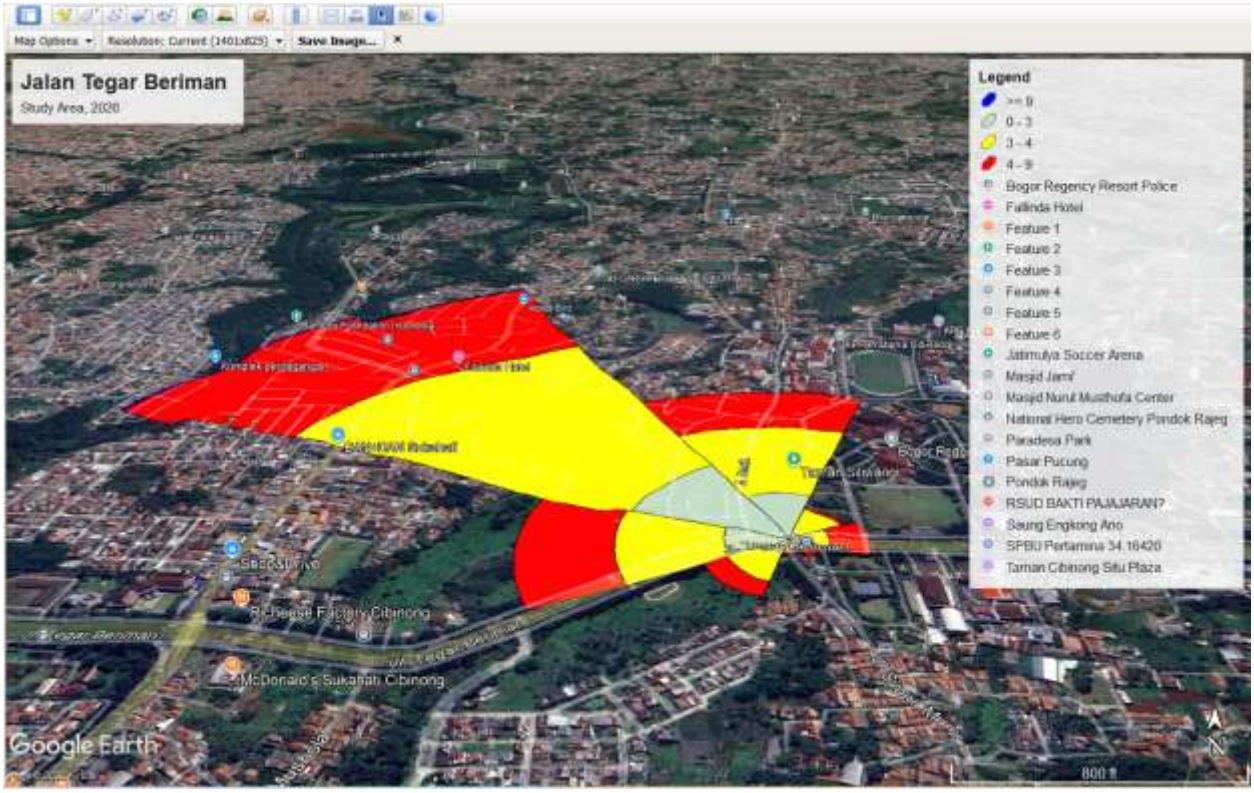


Fig 4. Visualization of Potential Pollutant Dispersion Paths Based on Dominant Wind Patterns on Jalan Tegar Beriman, Bogor Regency
Source: Resulted by WRPLOT View and Google Earth Pro (2026)

Environmental and Policy Implications. The findings indicate that areas located in the southeast (SE) direction should be prioritized for air pollution control. Mitigation strategies may include traffic management, urban vegetation development, and spatial-based air quality monitoring (Nasution et al., 2021). Integrating meteorological data into environmental policy can further enhance the effectiveness of air pollution control measures (Kusuma et al., 2022).

Scientific Contribution and Limitations. This study contributes to the integration of meteorological analysis and air pollution assessment at the local road-corridor scale. This approach complements previous studies that have predominantly focused on regional or industrial scales (Hidayat et al., 2023). However, this study has limitations, as it does not incorporate direct pollutant concentration data and does not account for micro-scale factors such as urban canopy structure and local turbulence (Seinfeld & Pandis, 2020). Therefore, future research is recommended to apply dispersion models such as AERMOD or CALPUFF for a more comprehensive analysis.

4. CONCLUSION

This study demonstrates that wind patterns along Tegar Beriman Road, Bogor Regency, have a clear dominant direction that can be used to identify potential dispersion pathways of vehicular pollution. Wind direction determines pollutant transport pathways, while wind speed influences dispersion or accumulation levels in ambient air. Downwind areas from emission sources have higher potential exposure and therefore require priority in air quality management. This study confirms that wind rose analysis using WRPlot View 8.0 is an effective approach for understanding meteorology-based pollutant dispersion dynamics, particularly at the preliminary analysis stage. Future studies should integrate pollutant concentration data and numerical dispersion models to provide more quantitative and comprehensive analyses.

DOI: http://dx.doi.org/10.36441/jamr

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support provided by the Institute for Research and Community Service (LPPM) Universitas Sahid through the internal research grant scheme, which significantly contributed to the successful completion of this study.

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