Vol. 16 No. 1 (2025) 70-77

Jurnal Riset
Teknologi Pencegahan Pencemaran Industri

Journal homepage: https://www.jrtppi.id

Spatial Analysis of Air Pollution Dispersion from a Stationary Source through Wind Profile: Case Study in North Sumatra

Yosef Barita Sar Manik[1], Aisyah Bestari Siswohartono[2], Aulia Rizqi Aufa Rafiqi[3], Brilian Maulani Putri[4], Daffa Renaldhi[5] Chaniago Mairuhu, Johanes Surya Utama Sede[6], Nati Nati[7]

[123456]Environmental Engineering, President University, Bekasi Regency, West Java

ARTICLE INFO

Article history:
Received: March, 29 2025
Received in revised form April, 29 2025
Accepted: May, 15 2025
Available online: May, 29 2025

Keywords:
Wind Rose
Air Pollutant
Wind Speed
Steel Industry
North Sumatra

ABSTRACT

The iron and steel industry constitutes one of the strategic pillars of economic development. However, it is also a major contributor to global air pollution due to high-temperature fossil fuel combustion inherent in its processes. This study aims to analyze the wind characteristics surrounding a steel and iron industrial facility in North Sumatra and to predict the areas most at risk from pollutant dispersion. Meteorological data from the NASA POWER Project database, covering the period from 2021 to 2024, were processed to examine local wind profiles across two distinct seasonal periods—rainy and dry. The analysis revealed that during the rainy season, winds predominantly originated from the northwest, with moderate speeds ranging from 2.10 to 3.60 m/s, leading to pollutant dispersion mainly toward the southeast (145°, 40%). Conversely, in the dry season, wind direction was more variable, as indicated by a low resultant vector percentage (11%), suggesting multidirectional pollutant spread. Across both seasons, the majority of wind speeds were below 2.10 m/s, which limits vertical atmospheric mixing and enhances pollutant retention near the surface. Air stagnation, particularly during transitional periods between seasons and under temperature inversion conditions, further intensifies pollutant accumulation. These findings underscore the critical role of seasonal wind dynamics in air pollution behavior and provide a scientific foundation for developing effective mitigation strategies. Practical policy implications include the establishment of buffer zones in downwind residential or agricultural areas, the implementation of stricter emission controls during periods of low wind speed and stagnation, and the integration of local wind data into early warning systems for air quality. Such measures are essential to protect public health, especially in high-density areas surrounding PT X, including Medan City, Deli Serdang Regency, Serdang Bedagai Regency, and Tebing Tinggi City.

1. INTRODUCTION

The iron and steel industry is a major global source of air pollution. Its processes—including sintering, coking, blast furnace operations, and electric smelting—emit hazardous gases such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon dioxide (CO_2), and fine particulate matter (PM2.5 and PM10) (Wu et al., 2024). These industries also release heavy metals like lead, cadmium, and mercury, along with volatile organic compounds (VOCs) (Y. Yang et al., 2023). The health effects include increased risks of respiratory and cardiovascular diseases, cancer, and premature mortality, while environmental impacts range from acid rain and soil degradation to climate change (Ren et al., 2023).

Meteorological conditions especially wind direction and speed play a key role in shaping pollutant dispersion. Wind direction determines the pollutant's trajectory from the emission source, while wind speed affects how far and

*Correspondence author.
E-mail: yosef.manik@president.ac.id (Yosef Manik)
doi: https://10.21771/jrtppi.2025.v16.no1.p70-77

Accreditation number: (Ristekdikti) 158/E/KPT/2021

fast pollutants spread. Low wind speeds tend to trap pollutants locally, whereas stronger winds disperse them over broader areas. Other atmospheric factors, such as turbulence and temperature inversions, can further intensify pollutant concentration at ground level (Jin et al., 2024).

Analyzing wind profiles helps identify areas most at risk from pollution exposure. Visualization tools like Wind Rose Diagrams allow researchers to examine wind direction and frequency over time, aiding in the mapping of pollution-prone zones. This information supports the development of mitigation strategies, placement of air quality monitoring stations, and environmental impact assessments (Amravati, 2020).

North Sumatra's wind dynamics are influenced by both monsoonal patterns and varied topography. Medan City, as a major industrial hub, hosts a steel plant in the Mabar area (3°40'14.09"N, 98°40'11.56"E). PT X was chosen as the study site due to its high emission profile, typical of the steel sector, and its proximity to densely populated areas (H. Yang et al., 2019).

Growing concern over air quality in Medan's industrial zones, particularly in metal and steel manufacturing, underscores the need for scientific assessment (Suryati et al., 2024). Data from the Central Bureau of Statistics (BPS) list several steel producers in the region known for significant emissions of particulates and gaseous pollutants (BPS Kota Medan, 2023; BPS Sumatera Utara, 2023). Although public records of pollution complaints are limited, the selection of PT X is justified by its industrial characteristics and the broader need for data-driven environmental evaluations. To date, no comprehensive study has assessed how local wind conditions influence pollutant dispersion from such industrial sources in Medan's urban setting.

This study aims to analyze wind patterns around PT X using Wind Rose Diagrams and resultant vector analysis based on 2021–2024 meteorological data. Seasonal influences, particularly the west (October–April) and east monsoons (April–October), are also considered in identifying dominant wind directions and high-risk exposure zones (Dehkhoda et al., 2024; Nufus & Nyoman Soemeinaboedhy, 2022) .

2. METHODS

This study uses a quantitative descriptive approach to examine wind behaviour around PT X in

Medan, with the aim of understanding potential pollutant dispersion patterns due to industrial emissions. The study is based on historical meteorological data from 2021 to 2024, supplemented by observation of geographic visual representation from software.

The primary analysis in this study involved the use of Wind Rose Diagrams to illustrate wind direction and frequency patterns based on historical meteorological data. Data collection and initial structuring were performed using spreadsheet tools, followed by wind pattern analysis and spatial visualization using specialized software. These tools supported the interpretation of pollutant dispersion relative to the industrial site and surrounding populated areas.

Time and Study Location

The observed data in this study span from January 2021 to December 2024, covering a complete range of seasonal changes, including both dry and rainy periods, which significantly affect wind behaviour and pollutant dispersion.

Based on satellite imagery from Google Earth, PT X is located at coordinates 3°40'14.09"N and 98°40'11.56" E, strategically located in an industrial area in Medan City, North Sumatra. As illustrated in **Figure 1**, PT X's location in Medan City, with its surrounding regencies or cities such as Deli Serdang Regency, Serdang Bedagai Regency, and Binjai City, and the surrounding areas, have varying population densities. This spatial variation highlights the importance of understanding wind-driven pollutant dispersion, as emissions from PT X have the potential to affect urban residential areas and surrounding areas, depending on seasonal wind behaviour.

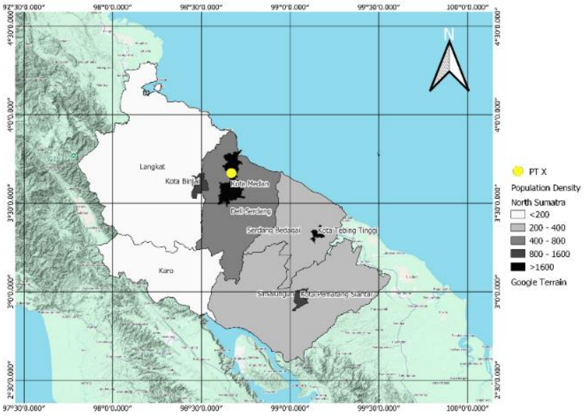

FIGURE 1. Population density in regencies and municipality surrounding PT X

Tools and Software

The tools and software utilized in this study were specifically selected to support the processes of data collection, processing, and visualization of wind characteristics in the vicinity of PT X. The tools employed include WRPLOT, Microsoft Excel, Google Earth Pro, and QGIS.

WRPLOT was used to generate wind rose diagrams and to visualize the distribution of wind speed and direction based on the meteorological dataset. Microsoft Excel was utilized to process and clean the meteorological data, including formatting date-time fields, filtering missing data, and performing basic statistical analyses. Google Earth Pro was employed to accurately determine the geographic coordinates and spatial characteristics of PT X and its surrounding area, providing essential spatial context for the pollutant dispersion analysis. In addition, QGIS was used to generate population density maps by integrating administrative boundary layers and population data, allowing spatial correlation between wind direction and potentially impacted residential zones to be assessed more clearly.

Type of Research

This study adopts a quantitative descriptive research design. The approach emphasizes the collection an numerical analysis of meteorological data, specifically wind speed and wind direction, to describe the patterns influencing pollutant dispersion around PT X. By using historical datasets from 2021 to 2024 and visualizing them through Wind Rose Diagrams, the research quantitatively characterizes wind behaviour without manipulating variables. The descriptive approach enables a structured presentation of wind patterns, which is essential for assessing the risks of pollutant dispersion based on observed environmental factors. This method is well-suited for the study's aim of providing a data-driven evaluation of pollutant spread, which can inform effective environmental management strategies (Huboyo et al., 2023)

Data Collection, Data Processing, and Analysis Methods

This study begins by collecting essential primary and secondary data to investigate wind patterns as the primary determinant of pollutant dispersion around PT X's industrial site. Meteorological data, specifically wind speed and direction, were obtained from the NASA/POWER database in CSV format. Using Microsoft Excel, the data were organized into columns representing date, time, wind speed, and wind direction. Subsequently, WR Plot software was employed to import the processed data and generate Wind Rose Diagrams, which depict the frequency distribution of wind directions and wind speeds during the study period (2021–2024), with accurate geographical coordinates recorded using Google Earth (Margareta Sitohang & Raflie Pahlevi, 2023)

Data visualization became a crucial step in intuitively understanding wind patterns. WRPLOT View software was utilized to generate wind rose diagrams that graphically represent the frequency and intensity of dominant wind directions. The data analysis conducted focused on interpreting wind patterns and their implications for pollutant dispersion.

Descriptive statistics provided a quantitative overview of wind speed characteristics at the study site. The frequency distribution of wind directions was analysed to identify the most frequent air movement directions. Wind rose diagrams served as the primary tool for understanding the dominant wind direction and the potential dispersion direction of pollutants from the PT X emission sources.

Overall, the research method—combining systematic data collection, structured processing, and the use of visual and analytical tools—provides a robust framework for understanding wind patterns around PT X and their role in pollutant dispersion. These methods form the foundation for analyzing pollutant distribution dynamics, which are further examined in the results and discussion sections. The findings contribute valuable insights into environmental and public health risks, and support the development of air pollution mitigation strategies tailored to local atmospheric conditions.

3. RESULT AND DISCUSSION

An analysis of wind direction and speed distribution was conducted at the study site, specifically around the steel plant stack located in Medan City (Latitude: 3°40'14.09"N, Longitude: 98°40'11.56"E), using historical meteorological data from 2021 to 2024. The goal was to identify the dominant wind direction and speed to understand the long-term trend of air movement and its implications for pollutant dispersion.

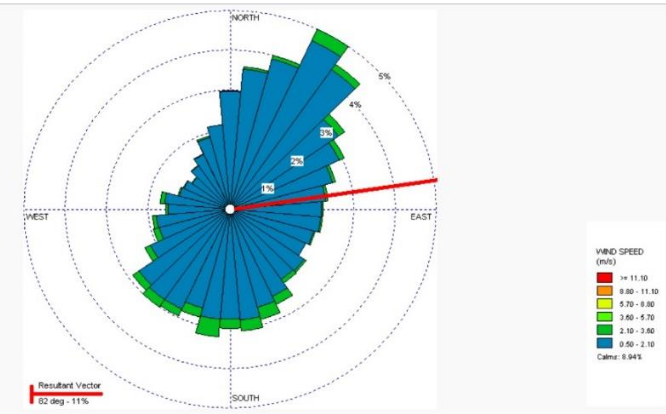

FIGURE 2. Resultant Wind Vector Dry Season

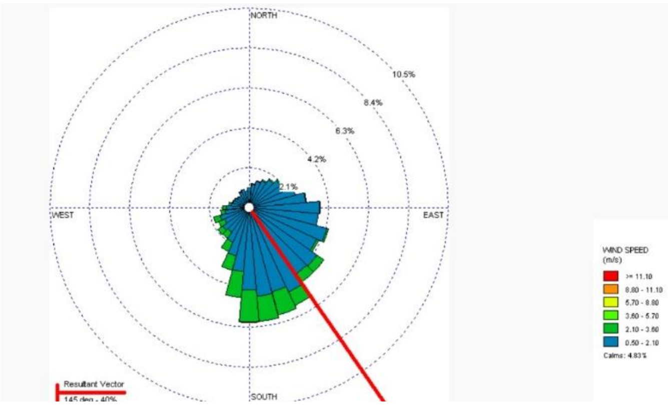

FIGURE 3. Resultant Wind Vector Rain season

The seasonal analysis of Windrose patterns and wind speed class frequency at the steel industry site in Medan reveals marked variations in meteorological behaviour between the wet and dry periods. During the rainy season, wind predominantly originated to the southeast quadrant, with a prevailing direction around 145° as shown in **Figure 3**, as indicated by a high resultant vector frequency of approximately 40%. Wind speed distribution in this season was skewed toward the lower to moderate range, with 83.7% of occurrences within 0.50–2.10 m/s and 11.4% within 2.10–3.60 m/s.

In contrast, the dry season exhibited a noticeable shift in wind dynamics. The dominant wind direction transitioned to the east (approx. 82°) as shown in **Figure 2**, accompanied by a significant reduction in directional consistency, as shown by a lower resultant vector of only 11%. Wind velocities during this period were more stagnant, with 86.7% of the measurements concentrated in the 0.50–2.10 m/s range and only 4.4% exceeding 2.10 m/s.

From a micrometeorological perspective, wind speed distribution significantly influences both vertical and horizontal mixing of pollutants within the atmospheric boundary layer. Low wind speeds (<2.10 m/s), which are prevalent in both wet and dry seasons, are typically associated with weak turbulence and limited dispersion capacity. During the rainy season, a slightly higher occurrence of moderate wind speeds (2.10–3.60 m/s) suggests intermittent enhancements in atmospheric mixing. Conversely, the dominance of calm conditions in the dry season further restricts pollutant dilution. These variations in the kinetic energy of air masses affect the mechanical turbulence necessary for effective pollutant transport (Li et al., 2022)

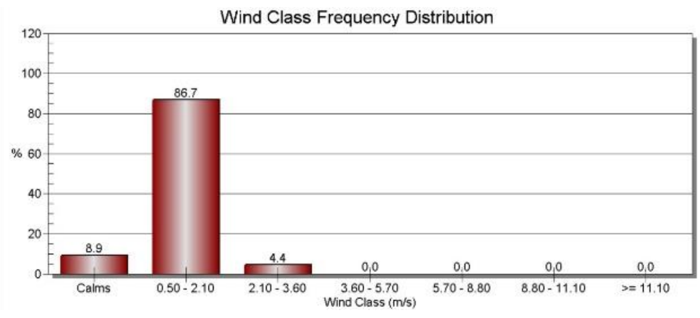

FIGURE 6. Wind Class Frequency Distribution Dry Season

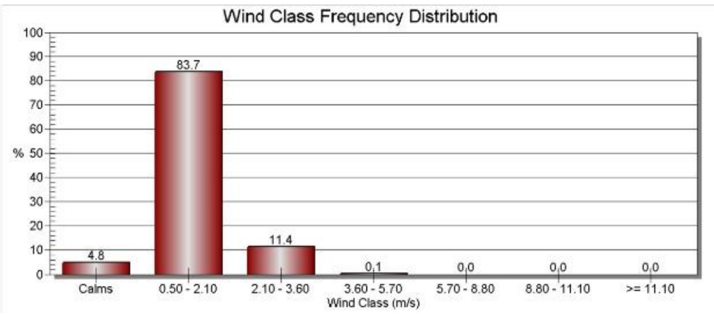

FIGURE 7. Wind Class Frequency Distribution Rain Season

Seasonal variations significantly influence the dispersion behaviour of air pollutants emitted from industrial sources. During the wet season, relatively consistent southeasterly winds and moderate wind speeds promote more effective advective transport, allowing emissions to spread farther from their origin and dilute over a wider area. This process can mitigate localized pollution buildup but may shift the affected zone, particularly if residential or ecological receptors are located downwind (Huboyo et al., 2023)

In the dry season, weaker and more variable wind conditions greatly limit the capacity for pollutant dispersion. Reduced atmospheric movement leads to the accumulation of emissions near their source, increasing ground-level pollutant concentrations. These meteorological conditions can intensify local air quality deterioration, particularly in cases of continuous, uncontrolled emissions. Therefore, such seasonal atmospheric limitations should be integrated into environmental risk evaluations and the planning of emission mitigation strategies (Augustin et al., 2020)

Discussion

During the dry season (April-October), the wind direction around PT X does not show strong consistency in one particular direction. Although the resultant vector value shows a tendency to the east (around 82°) with a strength of 11%, the wind direction distribution appears to be spread out to various sectors. This indicates that the dispersion potential of air pollutants is also diffuse, with the main direction covering most of Medan City and Deli Serdang Regency. With 86.7% of wind speeds in the low range (0.50-2.10 m/s) and only 4.4% exceeding 2.10 m/s, there is limited atmospheric mixing both horizontally and vertically. This condition allows pollutants to accumulate around emission sources, increasing exposure risks especially in dense residential areas such as Medan Tembung, Medan Timur, and Medan Perjuangan, where natural ventilation is also minimal.

In contrast, during the rainy season (October-April), the wind direction is more concentrated with a dominant pattern to the southeast (around 145°), supported by a stronger vector resultant of 40%. This seasonal wind pattern indicates the potential for emission dispersion specifically towards the western Deli Serdang Regency, Serdang Bedagai Regency, and Tebing Tinggi City. These areas include densely populated pockets, such as Percut Sei Tuan, Pematang Johar and Batang Kuis, which fall into the medium to high density category (618-2,779 people/km²). Although most wind speeds remained low (83.7% in the range of 0.50-2.10 m/s), the 11.4% increase in moderate winds (in the range of 2.10-3.60 m/s) increased the potential for pollutants to spread more widely than in the dry season. However, this consistent distribution pattern also increases the risk of long-term exposure accumulation in downwind areas (Huboyo et al., 2023).

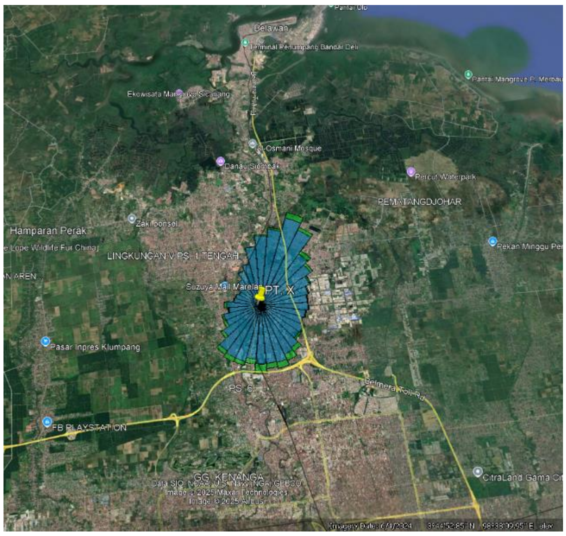

FIGURE 8. Dry Season Wind Overlay

Atmospheric stagnation conditions are also a concern, especially during the transition period between seasons, where the frequency of calm winds (<0.5 m/s) tends to increase. These events often coincide with temperature inversions, especially during the morning and evening hours, resulting in the accumulation of pollutants near the ground surface. Nearby areas such as Mabar, Medan Deli, and Medan Labuhan become particularly vulnerable to short-term spikes in pollution exposure, which can exacerbate respiratory and cardiovascular health risks for residents (Hellan et al., 2020).

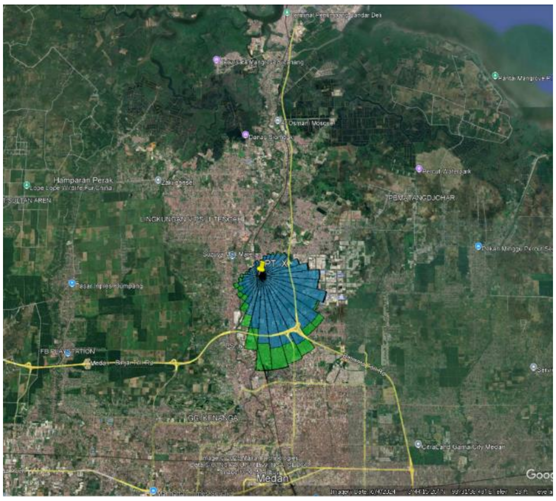

FIGURE 9. Rain Season Wind Overlay

Given that the affected areas are densely populated and intersect with key seasonal wind dispersion pathways, emissions from PT X pose substantial environmental and health risks. Therefore, targeted mitigation efforts are necessary. From the industry side, PT X must ensure continuous compliance with air emission standards and operate a real-time monitoring system using Continuous Emission Monitoring System (CEMS), as mandated by regulations (Kepmen LH No.13, 1995; Permen LHK No.13, 2021). Concurrently, the government should enhance the frequency and transparency of environmental monitoring, and enforce corrective actions in line with national provisions (UU No.32, 2009).

Spatially, based on prevailing wind patterns especially during the rainy season when pollutants predominantly disperse toward the southeast priority placement of air quality monitoring stations should be directed to southeastern Medan and the western region of Deli Serdang. These areas are most susceptible to pollutant accumulation and should be the focus of early warning systems and location-specific mitigation policies (Lapere et al., 2021).

4. CONCLUSION

This study reveals that seasonal wind patterns around PT X strongly influence the dispersion of industrial air pollutants. During the dry season, emissions are primarily directed toward the densely populated eastern districts of Medan (2,779–8,902 people/km²), whereas in the rainy season, pollutants are transported to moderately populated areas in Deli Serdang Regency (618–2,779 people/km²). Although wind speeds are slightly stronger in the rainy season, they provide limited improvement in dispersion. The overall dominance of low wind velocities (<2.10 m/s) in both seasons restricts pollutant dilution and increases the risk of accumulation near residential zones. Calm conditions during transitional months, combined with temperature inversion phenomena, further exacerbate exposure risks, particularly in densely populated areas near the emission source such as Mabar and Medan Deli.

These findings highlight the need for adaptive air quality management strategies. Specifically, seasonal wind behavior should guide the spatial placement of monitoring stations and inform localized pollution control interventions. By aligning policy and monitoring efforts with wind-driven dispersion patterns, decision-makers can better protect public health in densely populated, industrially active urban environments.

REFERENCE

Amravati, in. (2020). Application of Wind Rose model in Environmental Impact Assessment of Air Quality in Amravati. In *JETIRDI06020 Journal of Emerging Technologies and Innovative Research* (Vol. 7). JETIR. www.jetir.org

Augustin, P., Billet, S., Crumeyrolle, S., Deboudt, K., Dieudonné, E., Flament, P., Fourmentin, M., Guilbaud, S., Hanoune, B., Landkocz, Y., Méausoone, C., Roy, S., Schmitt, F. G., Sentchev, A., & Sokolov, A. (2020). Impact of sea breeze dynamics on atmospheric pollutants and their toxicity in industrial and urban coastal environments. *Remote Sensing*, *12*(4). https://doi.org/10.3390/rs12040648

BPS Kota Medan. (2023). *Direktori Industri Besar dan Sedang Kota Medan 2023*.

BPS Sumatera Utara. (2023). *Direktori Perusahaan Industri Manufaktur Provinsi Sumatera Utara 2023*.

Dehkhoda, N., Sim, J., Shin, J., Joo, S., Cho, S. H., Kim, J. H., & Noh, Y. (2024). Air Pollution Measurement and Dispersion Simulation Using Remote and In Situ Monitoring Technologies in an Industrial Complex in Busan, South Korea. *Sensors*, *24*(23). https://doi.org/10.3390/s24237836

Hellan, S. P., Lucas, C. G., & Goddard, N. H. (2020). *Optimising Placement of Pollution Sensors in Windy Environments*. http://arxiv.org/abs/2012.10770

Huboyo, H. S., Khasanah, N., Samadikun, B. P., & Astuti, W. (2023). Study of the dispersion of particulate emissions from industrial areas and its impact on surrounding residential areas. *IOP Conference Series: Earth and Environmental Science*, *1268*(1). https://doi.org/10.1088/1755-1315/1268/1/012070

Jin, M.-Y., Zhang, L.-Y., Peng, Z.-R., He, H.-D., Kumar, P., & Gallagher, J. (2024). The impact of dynamic traffic and wind conditions on green infrastructure performance to improve local air quality. *Science of The Total Environment*, *917*, 170211. https://doi.org/https://doi.org/10.1016/j.scitotenv.2024.170211

Kepmen LH No.13. (1995). *Keputusan Menteri Negara Lingkungan Hidup No. 13 Tahun 1995 Tentang : Baku Mutu Emisi Sumber Tidak Bergerak*.

Lapere, R., Menut, L., Mailler, S., & Huneeus, N. (2021). Seasonal variation in atmospheric pollutants transport in central Chile: Dynamics and consequences. *Atmospheric Chemistry and Physics*, *21*(8), 6431–6454. https://doi.org/10.5194/acp-21-6431-2021

Li, Z., Tanzer-Gruener, R., Presto, A., Adams, P., & Singh, S. (2022). *Simulations of near-source wind development and pollution dispersion over complex terrain under different thermal conditions*. http://arxiv.org/abs/2211.07050

Margareta Sitohang, R., & Raflie Pahlevi, A. (2023). Visualisasi Perbandingan Data Angin Observasi dan Data Model INA-WAVE dengan Metode Wind Rose Menggunakan Software WRPLOT Comparative Visualization of Wind Data Observation and INA-WAVE Model Data with Wind Rose Method Using WRPLOT Software. In *JULI* (Vol. 4, Issue 4).

Nufus, H., & Nyoman Soemeinaboedhy, I. (2022). *Pengaruh Angin Muson Australia Terhadap Sifat Hujan Pada Musim Kemarau di Wilayah Lombok The Influence of the Australian Monsoon Wind on the Characteristic of Rain in the Dry Season in the Lombok Region*. https://power.larc.nasa.gov/data-acces-viewer/.

Permen LHK No.13. (2021). *Peraturan Menteri Lingkungan Hidup dan Kehutanan Republik Indonesia Nomor 13 Tahun 2021 Tentang: Sistem Informasi Pemantauan Emisi Industri Secara Terus Menerus*. www.peraturan.go.id

Ren, H., Dong, W., Zhang, Q., & Cheng, J. (2023). Identification of priority pollutants at an integrated iron and steel facility based on environmental and health impacts in the Yangtze River Delta region, China. *Ecotoxicology and Environmental Safety*, *264*. https://doi.org/10.1016/j.ecoenv.2023.115464

Suryati, I., Hasibuan, N. H., Silalahi, R. A., Malau, R., & Tambun, Y. (2024). Microplastic Distribution Model in Ambient Air PM2.5Around the Medan Industrial Area, North Sumatra. *E3S Web of Conferences*, *519*. https://doi.org/10.1051/e3sconf/202451903014

UU No.32. (2009). *Undang-Undang Republik Indonesia Nomor 32 Tahun 2009 Tentang Perlindungan dan Pengelolaan Lingkungan Hidup*.

Yang, H., Tao, W., Liu, Y., Qiu, M., Liu, J., Jiang, K., Yi, K., Xiao, Y., & Tao, S. (2019). The contribution of the Beijing, Tianjin and Hebei region's iron and steel industry to local air pollution in winter. *Environmental Pollution*, *245*, 1095–1106. https://doi.org/https://doi.org/10.1016/j.envpol.2018.11.088

Yang, Y., Shen, J., Chen, H., Liang, Z., Liu, X., & Ji, H. (2023). Emission inventories, emission factors, and composition profiles of volatile organic compounds (VOCs) and heavy metals (HMs) from an e-waste dismantling park in southern China. *Environmental Pollution*, *331*, 121890. https://doi.org/https://doi.org/10.1016/j.envpol.2023.121890