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RESEARCH ARTICLE

Air Pollution Dispersion Analysis and Wind Resource Characterization in Coastal Bengkulu Using Meteorological Observation Data of 2021-2024

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Abstract

Air pollution risk in coastal Bengkulu, influenced by monsoonal system-shifting wind patterns and increasing anthropogenic necessitates, requires wind pattern analysis at the areas of Muko-Muko, Pulau Baai, and Seluma, which are influenced by open land, airport activities, industrial emissions, and marine-terrestrial interactions, which require WRPlot for accurate dispersion simulation and eco-friendly spatial planning. The aim of this study is to examine the characteristics of the wind and prevailing directions of dispersion in three selected points that represents pollution-prone area at coastal regions of Bengkulu Province: Muko-Muko, Baai Island, and Seluma. The data analysis involved processing daily wind speed and direction hourly data obtained from NASA's POWER period of 2021 to 2024. Wind rose plots of directional frequencies and distributions of the wind classes were created using WRPlot 8.0.2. Results indicate predominant wind directions at all three selected points are 57% of the resultant vector during dry season and 68% of the resultant vector during wet season, with wind speeds ranging from 0.50 to 2.10 m/s, accounting for up to 88.4% of records. Calms varied from 3.1% to 10.8%, and wind speeds above 5.70 m/s were not recorded. These findings suggest that Bengkulu's coastal wind regime is characterized by persistently light winds. Although such conditions limit the potential for large-scale wind energy utilization, they play a critical role in air pollution dispersion modelling and environmental risk assessment.

Keywords: Wind rose Analysis, WRPlot, Bengkulu, Seasonal Wind, Wind Speed Distribution

1. Introduction

Bengkulu, along the western coast of Sumatra in Indonesia, is exposed to fluctuating winds both because of local geographic variables as well as greater climatic cycles such as the storm (Agustin et al., 2025; Oktavia et al., 2023). The tropical and coastal area of Bengkulu makes day and regular wind flow change, which are significant variables in environmental modelling as well as hazard chance assessment (Winarso, 2017; Zolkefli and Hashim, 2021a) Accurate description of such wind regimes is essential in various environmental and development activities, for example, site screening for wind energy (Castelao and Barth, 2006; Whittaker et al., 2025),modelling dispersion of air pollution, and management of coastlines (Abdillah et al., 2022; Ondara et al., 2020). In addition, wind characteristics strongly influence the dispersion of air pollutants, where low wind speeds may inhibit dispersion and lead to pollutant accumulation near ground level, increasing risks to public health (Dwi et al., 2022; Jannah et al., 2024; Kebe et al., 2025; Qalbi et al., 2024).

Wind rose analysis would be a powerful tool in the natural sciences and particularly in wind characterization and interpreting their implications to regulate air quality, plan for renewable energy utilization, and regulate disasters (Manik et al., 2025; Ortiz et al., 2021; Sirait et al., 2023). In subsequent long decades, the application of specialized packages such as WRPlot has improved accuracy and efficiency of generating Wind rose charts (Felix et al., 2018). WRPlot reimagines wind speed and direction frequency visualization as a non-replacement tool in the hands of environmental analysts and engineers (Keintjem et al., 2023).

This research focuses on three observation points in Bengkulu Province, namely Muko-Muko, Pulau Baai, and Seluma. These observation points were selected because of their specific environmental conditions influencing wind behavior. Moku-Moku, situated near an airport, is noted for highly variable wind dispersion due to available open land and aviation activities (Handayani Sri and Ariska Yesi Indian, 2020). Pulau Baai, a coastal region near a coal-fired power plant (PLTU), offers a particular setting where coastal and industrial factors are combined (Heriyanto et al., 2021). On the other hand, Seluma is a low-lying coastal region with relatively flat topography, whose wind regimes are defined by marine and terrestrial factors (Mulyasari et al., 2022).

The selection of these three locations is driven by both scientific requirement and strategic importance. Each site has a distinct environmental setting that captures the heterogeneity of wind pattern over Bengkulu. Muko-Muko is a relatively underdeveloped northern area, useful for capturing baseline atmospheric dynamics with negligible urban contamination. Pulau Baai is a unique case in that it is within industrial proximity, which can significantly impact local wind dynamics and pollutant dispersion.

Hence its importance in air quality and public health studies. Seluma, with its flat coastal plain, is also highly sensitive to marine influences and has the potential to exhibit varying coastal wind dynamics under pressure from climate variability. All these locations facilitate a full understanding of wind regimes in the province, which is essential for regional planning, renewable energy potential, disaster risk management, and sustainable coastal development . This issue requires careful attention; therefore, an initial step in mitigating hydrometeorological disasters is to monitor meteorological parameters in the northern coastal region of Java Island, particularly wind conditions (Ma'rufatin et al., 2024a, 2024b). Furthermore, understanding wind regimes also supports the assessment of renewable energy feasibility, where low and stable wind conditions may limit large-scale wind power development but still allow small-scale applications (Rahim et al., 2023).

With wind conditions from these three stations plotted using WRPlot software, this study aims to generate Wind rose plots showing prevailing directions and magnitudes of dominant winds. These diagrams are expected to provide important information in Bengkulu local climatology and aid in informed decision-making for environmental planning, air quality management, and sustainable development strategies.

Wind rose analysis comes in handy when determining the prevailing wind directions, something that is crucial in various environmental studies including air quality determination, pollution dispersion modeling, and building design (Gede Yamuna Ceswaraningrat et al., 2024; Prasetiyo, 2024; Zolkefli and Hashim, 2021b). At the same time, the frequency distribution of wind classes gives information on wind speed frequency, making it possible to assess the probable energy output in wind farms or calculate safety requirements for buildings and structures subjected to high winds. The main objective in this study is:

1) To investigate the wind patterns and atmospheric characteristics in the coastal region of Bengkulu.
2) To identify the potential pollutant dispersion directions based on the prevailing wind patterns in the coastal region of Bengkulu.

2. Method

2.1 Data Collection

The wind direction and speed data used in this study were obtained from the POWER Data Access Viewer website (https://power.larc.nasa.gov/) (NASA, 2025) which is a database available and accessible from NASA. The data collected covers the area of Bengkulu Province, Indonesia, with a time span from two seasons, the wet season and the dry season. The data was downloaded in Excel format for further processing and analysis. This dataset contains daily records of wind direction and speed, which are important parameters in assessing wind energy potential and for environmental modeling purposes. This use of data obtained from satellites by NASA and the modeling results are likely to be consistent throughout the study period (Velázquez et al., 2011).

2.2 Data Processing

The original wind data from the POWER data access viewer website was recorded in Microsoft Excel format and then converted to the same format to be executed in the WRplot version 8.0.2 program. The Wind rose diagram graphed in this study is divided into seasonal periods to determine the wind direction and speed distribution each month. Seasonal period grouping is determined by BMKG data, where the rainy season typically occurs between December and February (Prasetyaningtyas, 2024), and the dry season between June and August (Prasetyaningtyas 2024b) Daily wind direction and speed data are processed by grouping the direction into eight cardinal directions, namely North, Northeast, East, Southeast, South, Southwest, West, Northwest. While the wind direction speed is categorized into six classes i.e., 0.50–2.10 m/s, 2.10–3.60 m/s, 3.60–5.70 m/s, 5.70–8.80 m/s, 8.80–11.10 m/s, and ≥ 11.10 m/s. The study area of these wind data is Pulau Moku-Moku, Baai Island, and Seluma, which latitudes range from around 3°17' to 4°00' South and longitudes range from 102°15' to 104°10' East, indicating clearly the geographical background of the data.

3. Result and Discussion

3.1 Data Analysis

The wind data used is wind direction and speed data according to two different seasons, the wet season that starts in December until January, and the dry season that starts in June until August. The data is presented in the form of yearly data and then averaged per month. Wind speed potential starts with averaging monthly data throughout the year to get an overview of wind direction and speed. From the data obtained, the average, maximum, minimum wind speed of each month can be determined.

To further support the analysis, wind rose diagrams are used to understand local wind patterns, which are important for energy planning, air quality management, and environmental disaster mitigation. Complementary monthly wind speed statistics (2021-2024) are also presented, illustrating the fluctuations of wind speed throughout the year.

Table 1 below summarizes the annual average wind speed during the wet season in Muko Muko from 2021 to 2024, showing variations across months and years.

Table. 1 Summary of the annual wind speed on wet season (2021-2024) on Muko Muko,

Season	Month	Year	V Average (m/s)
Wet 2021 – 2022	December	2021	6.75
	January	2022	6.87
	February	2022	7.09
Wet 2022 – 2023	December	2022	7.60
	January	2023	8.45
	February	2023	7.92
Wet 2023 – 2024	December	2023	7.88
	January	2024	7.69
	February	2024	7.79

Table 2 below summarizes the annual average wind speed during the dry season in Muko Muko from 2021 to 2024, showing variations across months and years.

Table. 2 Summary of annual wind speed on dry season (2021-2024) on Muko Muko,

Season	Month	Year	V Average (m/s)
Dry 2021 – 2022	June	2021	9.15
	July	2022	8.15
	August	2022	9.21
Dry 2022 – 2023	June	2022	9.78
	July	2023	9.22
	August	2023	8.21
Dry 2023 – 2024	June	2023	9.38
	July	2024	9.08
	August	2024	8.32

Table 3 below summarizes the annual average wind speed during the wet season in the Baai Island from 2021 to 2024, showing variations across months and years.

Table 3. Summary of annual wind speed on wet season (2021-2024) in the Baai Island

Season	Month	Year	V Average (m/s)
Wet 2021 – 2022	December	2021	3.37
	January	2022	2.91
	February	2022	3.41
Wet 2022 – 2023	December	2022	3.81
	January	2023	3.77
	February	2023	4.24
Wet 2023 – 2024	December	2023	2.98
	January	2024	2.52
	February	2024	2.56

Table 4 below summarizes the annual average wind speed during the dry season in the Baai Island from 2021 to 2024, showing variations across months and years.

Table 4. Summary of annual wind speed on dry season (June – August) in the Baai Island

Season	Month	Year	V Average (m/s)
Dry 2021 – 2022	June	2021	2.88
	July	2022	2.61
	August	2022	3.17
Dry 2022 – 2023	June	2022	3.27
	July	2023	3.39
	August	2023	4.40
Dry 2023 – 2024	June	2023	2.62
	July	2024	3.55
	August	2024	3.93

Table 5 below summarizes the annual average wind speed during the wet season in Seluma from 2021 to 2024, showing variations across months and years.

Table 5. Summary of annual wind speed on wet season (December – February) in Seluma

Season	Month	Year	V Average (m/s)
Wet 2021 – 2022	December	2021	4.18
	January	2022	3.52
	February	2022	4.45
Wet 2022 – 2023	December	2022	4.95
	January	2023	5.01
	February	2023	5.92
Wet 2023 – 2024	December	2023	4.30
	January	2024	3.05
	February	2024	3.25

Table 6 below summarizes the annual average wind speed during the dry season in Seluma from 2021 to 2024, showing variations across months and years.

Table 6. Summary of annual wind speed on dry season (June – August) in Seluma

Season	Month	Year	V Average (m/s)
Dry 2021 – 2022	December	2021	3.63
	January	2022	3.57
	February	2022	4.73
Dry 2022 – 2023	December	2022	5.14
	January	2023	5.56
	February	2023	7.14
Dry 2023 – 2024	December	2023	3.70
	January	2024	5.35
	February	2024	7.14

3.2 Wind Rose Diagram Analysis

From Figure 1, it can be seen that the data retrieved was the wind data of Muko-Muko, Bengkulu during the wet season, which occurs from June to August. The diagram shows that the wind dominantly blows toward the west direction with a combination of three main wind speed ranges: 0.50–2.10 m/s, 2.10–3.60 m/s, and 3.60–5.70 m/s. The calm wind condition is minimal, with a calmness percentage of only 0.22%, indicating that wind activity is generally present during this period.

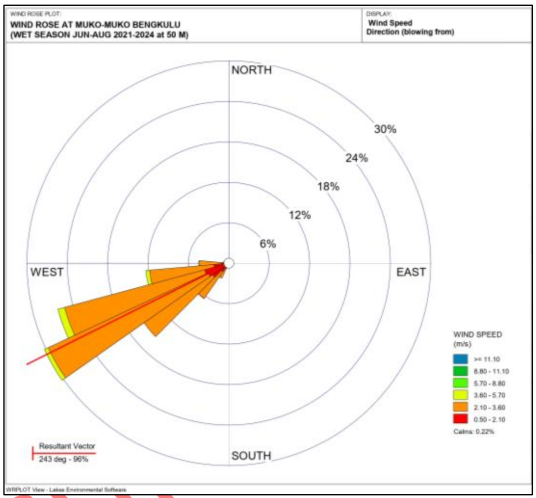

Fig.1 Muko Muko Wind rose Diagram in June – August in Year of 2021 – 2024

Additionally, the red arrow in the diagram is the resultant vector indicating prevailing mean direction and uniformity of wind flow. In this wind rose, the resultant vector is 243 degrees, or west-southwest (WSW) direction, and represents 96% of total wind activity. It reveals that wind patterns during the wet season are mainly uniform from the east-northeast and headed for the west-southwest. Identification of the resulting vector is critical in environmental planning, especially in evaluating pollutant dispersal, finding the optimal placement of wind turbines, and for the purpose of ensuring building construction to be capable of withstanding prevailing wind directions.

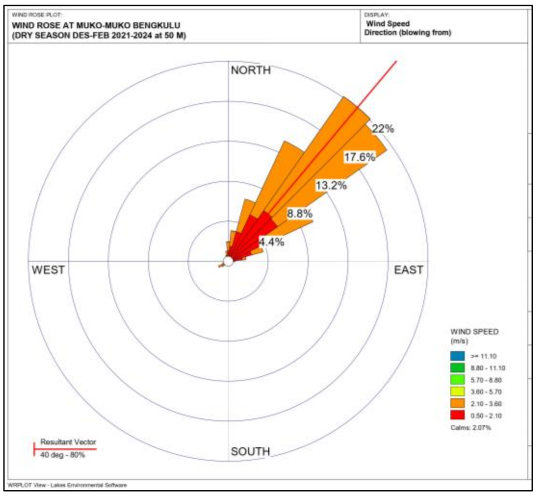

Fig.2 Muko Muko Wind rose Diagram in December – February in Year of 2021 – 2024

From figure 2, it can be seen the data that has been retrieved was the wind data of Muko Muko during the dry season, which occurs in December until February. In the diagram, it is concluded that the wind dominantly goes to the north with the mixture of three range wind speed of 0.50-2.10 m/s, and 2.10 - 3.60 m/s and with the wind calmness percentage is 0.22%.

In the December to February dry season wind rose diagram, the resultant vector is indicated by the red arrow and is employed to indicate the prevailing direction of the wind and overall trend of flow during the observation period. The resultant vector points at 40 degrees, which is a northeast (NE) direction. It represents 80% of the distribution of winds, so that a majority of winds during this season blow normally from the southwest towards the northeast.

This pattern indicates a prevailing direction of dominating winds, and this is important in the case of environmental concerns such as air pollution dispersion modeling, planning the layout of wind-sensitive facilities, and determining best location for wind energy systems. This vector's stability also means that wind action during the dry season is relatively stable and uniform in this region.

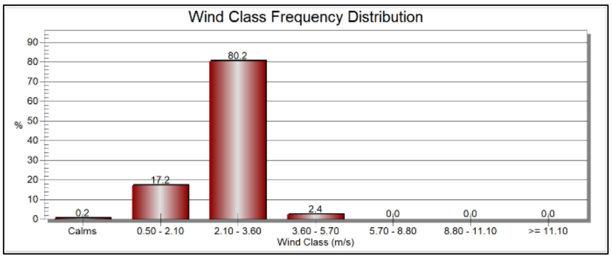

Fig. 3 Muko Muko Wind Class Frequency Distribution of Wet Season

According to figure 3, the most common wind speeds of 2.10–3.60 m/s, which comprise 80.2% of all observations made, are observed. Wind speeds 0.50–2.10 m/s were also highly common, composing 17.2% of the data. Conditions of calm or wind speeds near zero were recorded 0.2% of the time. Conversely, stronger wind speeds of 3.60–5.70 m/s were rarely experienced and only for 2.4% of the time. No speeds higher than 5.70 m/s were recorded within the observation period during wet season and dry season. These results indicate that the regime of the winds in the Muko Muko region is typically defined by low to moderate wind speeds with occasional occurrences of strong winds.

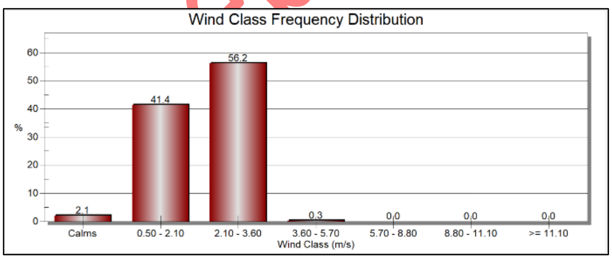

Fig. 4 Muko Muko Wind Class Frequency Distribution of Dry Season

According to figure 4, the most common wind speeds of 2.10–3.60 m/s, which comprise 56.2% of all observations made, are observed. Wind speeds 0.50–2.10 m/s were also highly common, composing 41.4% of the data. Conditions of calm or wind speeds near zero were recorded 2.1% of the time. Conversely, stronger wind speeds of 3.60–5.70 m/s were rarely experienced and only for 0.3% of the time. No speeds higher than 5.70 m/s were recorded within the observation period during wet season and dry season. These results indicate that the regime of the winds in the Muko Muko region is typically defined by low to moderate wind speeds with occasional occurrences of strong winds.

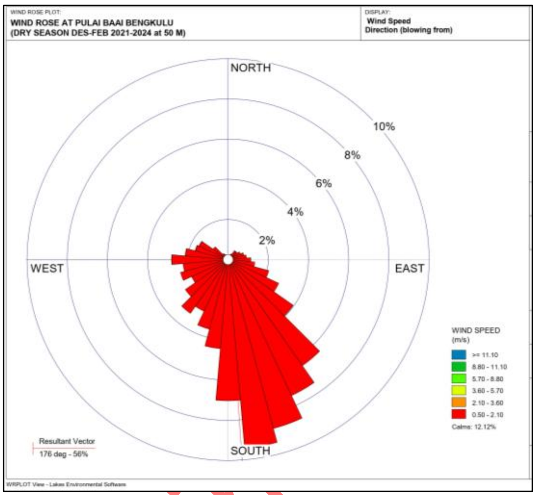

Fig 5. Baai Island Wind rose Diagram in June – August in Year of 2021 – 2024

From figure 5, it can be seen the data that has been retrieved was the wind data of Baai Island during the dry season, which occurs in June until August. In the diagram, it is concluded that the wind dominantly goes to the west with the mixture of three range wind speed of 0.50-2.10 m/s, and 2.10 - 3.60 m/s and with the wind calmness percentage is 9.60%.

Additionally, the resultant vector, as indicated by the red arrow, is 277 degrees, which is the direction of west and is 59% of the total wind distribution. This indicates that most of the wind during the wet season is from the east, blowing westwards. This prevailing wind direction is vital in planning that involves environmental impact assessments such as the dispersion of pollutants, the design of coastal structures, and the fitting of ventilation systems or wind turbines.

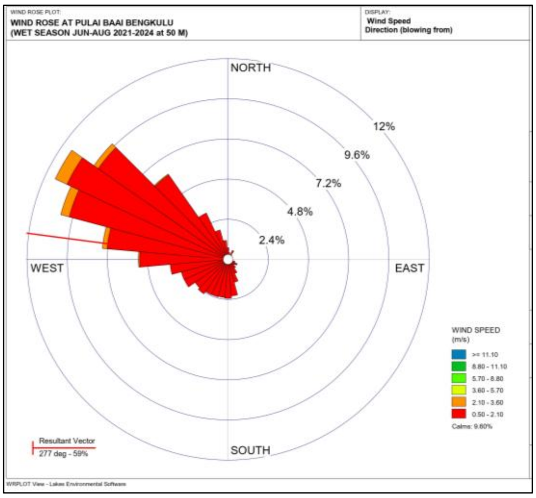

Fig 6. Baai Island Wind rose Diagram in December – February in Year of 2021 – 2024

From figure 6, it can be seen the data that has been retrieved was the wind data of Baai Island during the wet season, which occurs in December until February. In the diagram, it is concluded that the wind dominantly goes to the south and partially goes to the west with the wind speed of 0.50-2.10 m/s and with the wind calmness percentage is 12.12%.

The resulting vector, indicated on the chart by the red arrow, is 176 degrees and represents 56% of the total wind distribution. This shows that most of the dry-season wind is blowing from north to south (almost directly southward). 176 is the direction of origin of the wind (blowing from), so the wind is directed toward approximately true south.

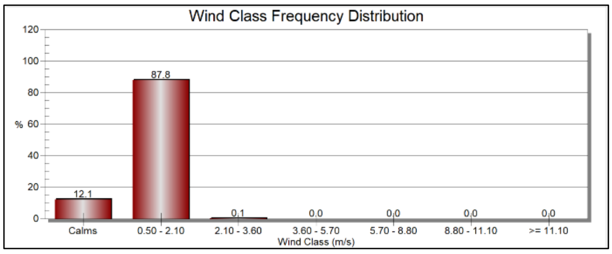

Fig 7. Baai Island Wind Class Frequency Distribution of Wet Season

From figure 7, it shows that the conditions of winds are predominantly characterized by very low wind speeds. Calm conditions were experienced 12.1% of the time, while winds between 0.50–2.10 m/s dominated 87.8% of the time, showing an overwhelming dominance of light winds. Wind speeds ranging from 2.10–3.60 m/s were only encountered 0.1% of the time. There were no wind readings above 3.60 m/s recorded during the monitoring period. These results suggest that Pulau Baai in general generally experiences very light to calm winds, with few occurrences of strong or moderate winds.

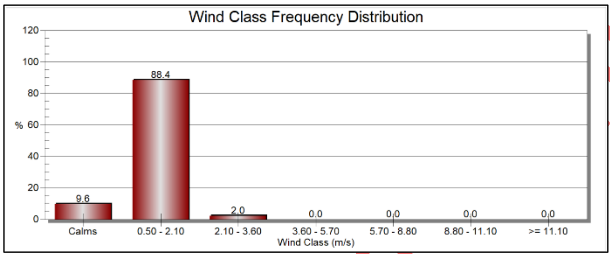

Fig 8. Baai Island Wind Class Frequency Distribution of Dry Season

From figure 8, it shows that the conditions of winds are predominantly characterized by very low wind speeds. Calm conditions were experienced 9.6% of the time, while winds between 0.50–2.10 m/s dominated 88.4% of the time, showing an overwhelming dominance of light winds. Wind speeds ranging from 2.10–3.60 m/s were only encountered 2.0% of the time. There were no wind readings above 3.60 m/s recorded during the monitoring period. These results suggest that Pulau Baai in general generally experiences very light to calm winds, with few occurrences of strong or moderate winds.

From figure 9, it can be seen the data that has been retrieved was the wind data of Seluma during the wet season, which occurs in June until August. In the diagram, it is concluded that the wind dominantly goes to the east and partially goes to the south with the mixture of two wind speed of 0.50 – 2.10 m/s and 2.10 – 3.60 m/s and with the wind calmness percentage is 5.92%.

The resultant vector, as indicated by the red arrow on the chart, has a direction of 169 degrees and accounts for 68% of the total wind distribution. This means that the majority of the wind during the wet season blows from the north towards the south-southeast. The value of 169 degrees represents the direction from which the wind originates (blowing from), indicating a consistent and dominant wind flow heading approximately southward.

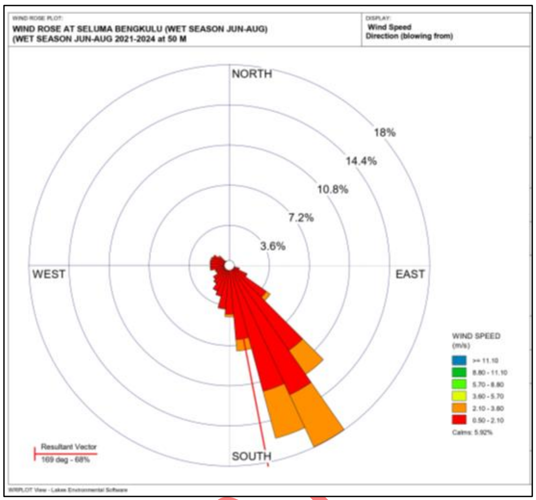

Fig 9. Seluma Wind rose Diagram in June – August in Year of 2021 – 2024

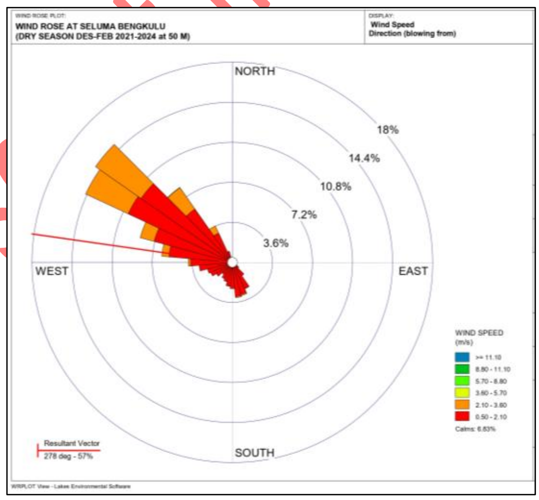

Fig 10. Seluma Wind rose Diagram in December – February in Year of 2021 – 2024

From figure 10, it can be seen the data that has been retrieved was the wind data of Seluma during the dry season, which occurs in December until February. In the diagram, it is concluded that the wind dominantly goes to the west and partially goes to the south with the mixture of two wind speed of 0.50 – 2.10 m/s and 2.10 – 3.60 m/s and with the wind calmness percentage is 6.83%.

The resultant vector, shown by the red arrow on the wind rose diagram, has a direction of 278 degrees and represents 57% of the total wind distribution. This indicates that during the dry season, most of the wind blows from the east towards the northwest. The direction of 278 degrees shows the origin of the wind, meaning the wind is heading roughly westward.

From figure 11, it shows that the conditions of winds are predominantly characterized by very low wind speeds. Calm conditions were experienced 5.9% of the time, while winds between 0.50–2.10 m/s dominated 79.4% of the time, showing an overwhelming dominance of light winds. Wind speeds ranging from 2.10–3.60 m/s were only encountered 14.7% of the time. There were no wind readings above 3.60 m/s recorded during the monitoring period. These results suggest that Seluma in general generally experiences very light to calm winds, with few occurrences of strong or moderate winds.

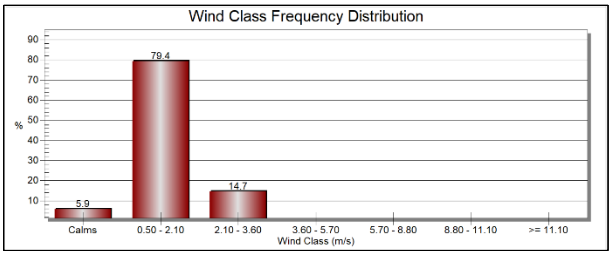

Fig 11. Seluma Wind Class Frequency Distribution of Wet Season

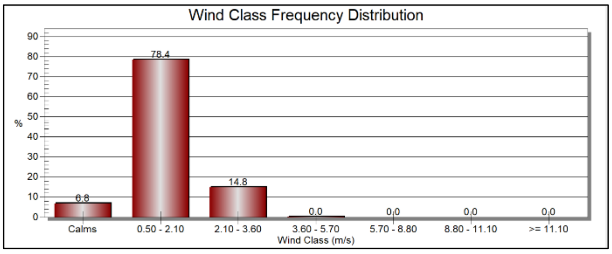

Fig 12. Seluma Wind Class Frequency Distribution of Dry Season

From figure 12, it shows that the conditions of winds are predominantly characterized by very low wind speeds. Calm conditions were experienced 6.6% of the time, while winds between 0.50–2.10 m/s dominated 78.4% of the time, showing an overwhelming dominance of light winds. Wind speeds ranging from 2.10–3.60 m/s were only encountered 14.8% of the time. There were no wind readings above 3.60 m/s recorded during the monitoring period. These results suggest that Seluma in general generally experiences very light to calm winds, with few occurrences of strong or moderate winds.

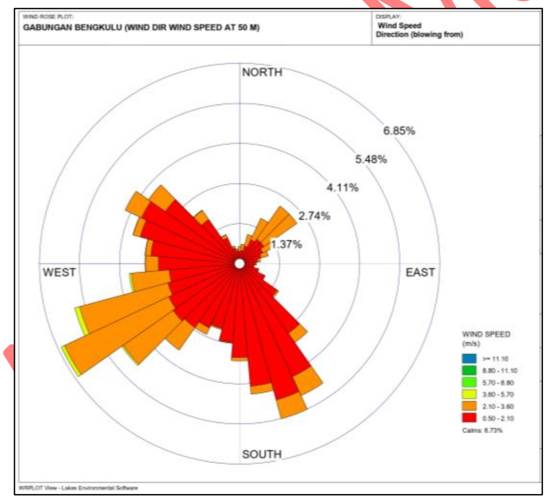

Fig 13. Combination of Muko Muko, Baai Island, Seluma Wind rose Diagram in Wet Season and Dry Season

From the figure 13, it can be observed that the wind data was recorded in Gabungan Bengkulu at a height of 50 meters. The diagram shows that during the observation period, the wind predominantly blew toward the west and southwest directions. The wind speeds were primarily within the ranges of 0.50–2.10 m/s and 2.10–3.60 m/s, with a smaller portion reaching up to 5.70 m/s. The percentage of wind calmness during this period was recorded at 7.37%, indicating relatively consistent wind movement.

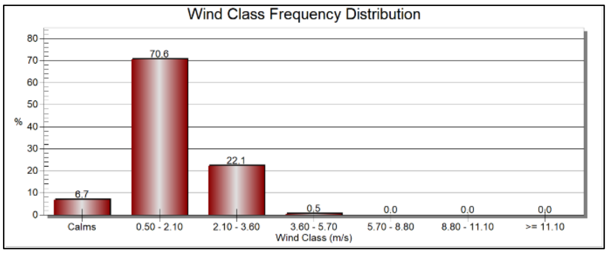

Fig 14. Combination of Muko Muko, Baai Island, Seluma Wind Class Frequency Distribution in Wet Season and Dry Season

From the figure 14, it shows that the wind conditions in Gabungan Bengkulu are predominantly characterized by very low wind speeds. Calm conditions occurred 6.7% of the time, while winds between 0.50–2.10 m/s dominated significantly at 70.6%, indicating a strong prevalence of light winds. Wind speeds in the range of 2.10–3.60 m/s were observed 22.1% of the time, while higher wind classes such as 3.60–5.70 m/s were rarely encountered at only 0.5%. There were no recorded wind speeds above 5.70 m/s during the monitoring period. These results indicate that the combination of the three regions are generally experiencing calm to light wind conditions, with very limited occurrences of stronger winds.

There were no significant occurrences of higher wind speeds (>5.70 m/s) observed over the observation period. This frequency indicates that the study area predominantly consists of light to moderate wind conditions, and this should be remembered for any environmental or energy use in the area.frequency ranging up to around 6.85%.

Wind speeds are generally low to moderate, mostly falling in the range of 0.5–3.6 m/s, as can be seen from the dominance of red and orange shades in the graph. Wind velocities above 5.7 m/s are very (Rahim et al., 2021). These results show that the Bengkulu region, as defined by these three sites of observation, is subject to frequent and relatively light winds, which have their origins in the southeastern quadrant (Manwell et al., n.d.)

4. Result and Discussion

This section introduces and describes the wind speed and direction data collected from three locations in Bengkulu Province: Seluma, Pulau Baai, and Muko Muko. The data, collected between 2021 and 2024 at 50 m using NASA POWER and processed by WRPlot and Google Earth, were divided into wet season (June–August) and dry season (December–February). Seasonal division enables smoother monitoring of monsoonal influences and coastal wind directions in different environmental conditions.

Results are illustrated by Wind rose diagrams and 3D spatial models to show statistical and geographic observations. Each of the subsections below gives a description of wind direction and speed by site and subsequent interpretation in terms of surrounding geographic and climatic conditions.

4.1 Muko Muko Wind Pattern

As seen in figure 15 and 16, the Muko Muko wind rose plots are more variable compared to the other stations. During the wet season, the wind blows in a predominantly northwest direction with slower wind speeds of 0.5–2.1 m/s (orange sectors predominant). This may be the result of land-sea thermal gradients, considering that the site is in proximity to an airport and open land.

Fig 15. Wind rose Visualization for Muko Muko During The Wet Season at 50 Meter Height Using Google Earth.

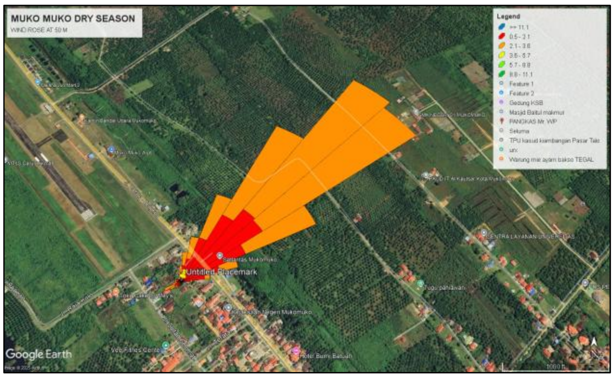

Fig 16. Wind rose Visualization for Muko Muko During The Dry Season at 50 Meter Height Using Google Earth.

During the dry season, the wind direction reverses directionally to the southwest and west, and the velocity slightly increases with a dominant appearance of the 0.5–2.1 m/s speed class (red bars). The transitional nature of the wind at Muko Muko can be a reflection of its semi-urban nature and sensitivity to natural and constructed environmental conditions. This situation indicates that the air pollution will be blown towards the plantation and rural residential areas to the east and southeast of the city, which has low health risks for human exposure.

Although there is a seasonal shift, the wind conditions remain moderate, with little to no threat to infrastructure or natural systems in the region.

4.2 Baai Island Wind Pattern

As seen in figure 17 and 18, the Baai Island, the pattern of wind is more consistent in both seasons. The dominant wind direction remains southwestward, likely because of its coastal-industrial site near the coal-fired power plant. Wind speeds are also very concentrated within the 2.1–3.6 m/s interval in both seasons, as reflected by the heavy red visualization in both plots.

The homogeneity of space means that Pulau Baai wind results from relatively stable atmospheric circulation and perhaps anthropogenic thermal activity from industrial buildings.

As the direction of the wind sweeps away air from housing estates and makes them point to the sea or industrial areas, the risk of dispersing air pollution to residential estates is negligible. Moreover, because the velocity of the wind is moderate, it is not strong enough to transport dust or contaminants over distances, thus the risk of exposure to the adjacent community would be negligible. The regularity of wind direction, moderate wind speed, and the industrial estate being relatively far from living quarters suggest that there is minimal health hazard due to air pollution transported by wind in Pulau Baai in general.

Because there are no higher wind classes and the velocities are not high, there is little chance of environmental disturbance by the wind in Baai Island.

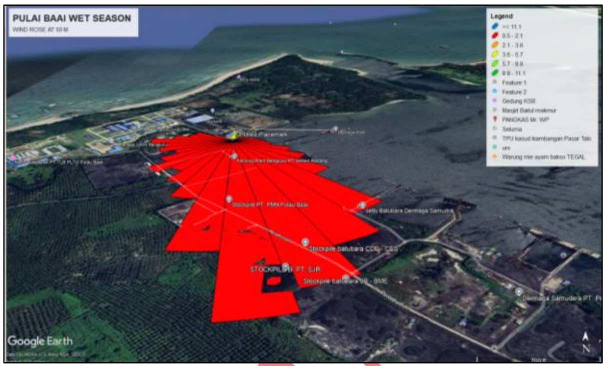

Fig 17. Wind rose Visualization for Baai Island During The Wet Season at 50 Meter Height Using Google Earth.

Fig 18. Wind rose Visualization for Baai Island During The Dry Season at 50 Meter Height Using Google Earth.

4.3 Seluma Wind Pattern

As seen in figure 19 and 20, the wind rose plot of Seluma shows a distinct seasonal contrast. During the wet season, the wind predominantly blows toward the east-southeast direction with wind speeds mostly ranging from 0.5–3.6 m/s, as evidenced by the dominance of red and orange color segments. The pattern reflects the influence of the southeast monsoon on Seluma's coast.

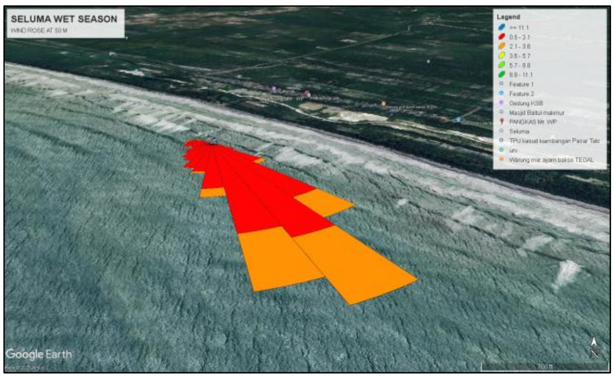

Fig 19. Wind rose Visualization for Seluma During The Wet Season at 50 Meter Height Using Google Earth.

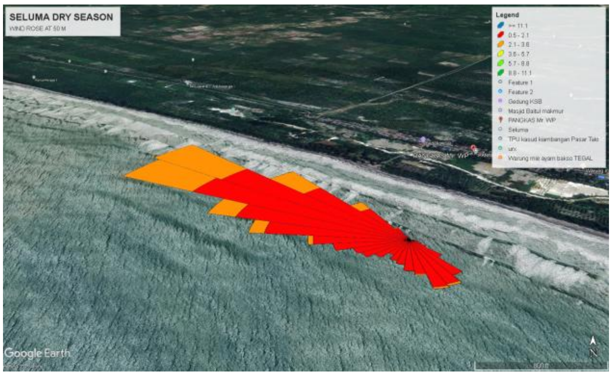

Fig 20. Wind rose Visualization for Seluma During The Dry Season at 50 Meter Height Using Google Earth.

In contrast, during the dry season, the wind direction is considerably altered to the west-southwest with the same classes of wind speed. The prevalence of light to calm winds shows that Seluma is influenced by a weakened monsoonal cycle with limited high wind activity.

These wind characteristics indicate that Seluma is not prone to extreme wind events throughout the year, and the environment is largely safe from wind disaster threats.

Furthermore, from an environmental health perspective, the wind flow toward rural and plantation areas during the dry season presents a low health risk to the population. Since the dominant wind carries any airborne pollutants away from denser urban zones and toward less populated agricultural zones, the potential for human exposure to harmful substances is reduced. However, special attention may still be required for agricultural productivity and sensitive ecosystems that lie downwind, as they may be more susceptible to the accumulation of dust, pesticide drift, or other particulate matter carried by prevailing winds.

5. Conclusion

The wind pattern characteristics in the coastal region of Bengkulu during the time span of this study were dominated by low wind speeds, generally ranging from 0.50–3.60 m/s, with no significant occurrences of strong winds (>5.70 m/s), indicating a relatively weak and stable wind regime.

In Muko-Muko, during the rainy season, wind speeds were dominated by the 0.50–3.60 m/s range with a resultant direction of approximately 243° (west-southwest), indicating wind flow from the northeast toward the southwest. Meanwhile, during the dry season, there is a significant change in wind direction with a resultant direction of 40° (northeast), indicating a wind flow from the southwest toward the northeast. This pattern reflects a fairly strong monsoon influence as well as more variable atmospheric dynamics compared to other locations.

On Baai Island, wind conditions tend to be more stable across seasons, with dominant speeds ranging from 0.50 to 2.10 m/s, occasionally reaching 2.10 to 3.60 m/s. During the dry season, the resultant direction of approximately 277° (west) indicates an east-to-west wind flow. Meanwhile, during the rainy season, the resultant direction is around 176° (south), indicating a flow from north to south. Although there are seasonal variations, the wind pattern generally remains consistent and relatively weak.

In Seluma, wind speeds are also dominated by the range of 0.50–3.60 m/s in both seasons. During the rainy season, the resultant direction is around 169° (southeast), indicating a wind flow from north to south, while during the dry season it shifts to 278° (west), indicating a flow from east to west. This pattern indicates moderate variability influenced by the interaction between coastal factors and the monsoon system.

Regarding the second objective different environmental risk indicators were identified at each location. In Muko-Muko, the direction of pollutant dispersion tends toward plantation areas and rural settlements in the eastern and southeastern parts. Although population density is relatively low, there remains a potential for exposure of agricultural land and local communities to pollutants, particularly because low wind speeds can hinder the dispersion process.

On Baai Island, pollutant dispersion is predominantly directed toward coastal and marine areas, away from densely populated residential zones. This indicates that the direct risk to human health is relatively low, but it poses potential impacts on marine ecosystems, particularly organisms such as phytoplankton, fish larvae, and benthic organisms, which are sensitive to pollutant deposition from industrial activities.

In Seluma, based on wind pattern analysis and spatial visualization, the direction of pollutant dispersion in both seasons tends to be toward coastal and marine areas. During the rainy season, winds carry pollutants toward the south–southeast sector, while during the dry season they shift toward the west, yet still show a tendency toward aquatic areas. These conditions indicate that the risk of direct human exposure is relatively low, but there is potential for impacts on marine and coastal ecosystems, particularly due to the deposition of pollutant particles that can affect phytoplankton, fish larvae, and benthic organisms, and potentially disrupt ecosystem balance in the long term.

This study contributes a comprehensive analysis of wind patterns and their impacts in the Bengkulu region. The findings of this study are expected to serve as a basis for the government in developing spatial and regional plans that are more adaptive to environmental conditions, as well as for the public as a source of information to understand the potential environmental impacts in the areas where they live.

For future research, it is recommended to integrate wind dispersion analysis with a detailed land-use mapping of the green open spaces to evaluate more specific impact of pollutants on vegetated areas such as green open spaces, mangrove forests, and agricultural land. Special attention should also be given to downwind ecosystems, including coastal and marine areas, which are potentially affected by pollutant deposition and may impact marine biodiversity. Additionally, the use of long-term data and high-resolution modelling (such as CFD or HYSPLIT) is recommended to improve the accuracy of pollutant dispersion predictions and support more sustainable environmental planning.

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