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Original Article

Analysis of Wind Speed and Direction Variability for a Preliminary Study of Wind Energy in Coastal Areas

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ABSTRACT
Wind variability in coastal areas is a key factor influencing regional climate patterns, ecosystem stability, and maritime activities. This study aims to analyze the variability of wind speed and direction in the coastal region of Paloh District, West Kalimantan, using the Weibull statistical distribution and Windrose diagrams. Wind data were obtained from the BMKG Meteorological Station in Paloh over a 15-year period (2009–2023). The results indicate significant seasonal variations in wind characteristics. The highest wind speeds occur in July, coinciding with the peak of the southeast monsoon season. Conversely, wind speeds tend to decrease during the transition seasons (March–May and September–November). Dominant wind directions also vary throughout the year, with southerly and southeasterly winds prevailing during the dry season (JJA) and northwesterly winds dominating during the rainy season (DJF). The Weibull shape parameter (k = 2.260) and scale parameter (c = 3.525) indicate relatively stable wind distribution in this region. These findings provide valuable insights into coastal wind variability, which is essential for climate modeling, coastal management, and the potential development of renewable energy, particularly wind energy, in West Kalimantan.

KEYWORDS
wind variability; weibull distribution; wind energy

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INTRODUCTION

Wind is one of the primary elements in the atmospheric system, playing a crucial role in regulating regional climate conditions and influencing various geophysical processes in coastal areas (Webster, 2020; Li et al., 2020; Asyam et al., 2024). Variations in wind speed and direction can impact ocean current patterns, sediment transport, and coastal ecosystem stability (Ganske et al., 2016; Zeng et al., 2019). Understanding wind variability is essential in the context of climatology, disaster mitigation, and wind-based renewable energy exploration (Harianto & Karjadi, 2024; Kaplan, 2020; Purba, 2014; Zhou et al., 2021). As the demand for clean and sustainable energy increases, studying wind patterns in various coastal regions becomes increasingly relevant for determining the potential for efficient and sustainable wind energy development (Asyiawati & Akliyah, 2011).

As an archipelagic country situated between the Indian Ocean and the Pacific Ocean, Indonesia's wind patterns are influenced by the monsoon system and ocean-atmosphere interactions (Aldrian, 2008; Haryanto et al., 2020). Periodic changes in wind direction and speed affect regional weather and climate dynamics, including precipitation, sea surface temperature, and evapotranspiration levels (Simanjuntak, 2022). Several studies have analyzed wind patterns in Indonesian waters, focusing on the impact of monsoons and seasonal variability on coastal atmospheric dynamics. A study conducted by Adriat et al. (2024) in the Samudera Indah waters, West Kalimantan, found that significant wave height and period were greater during the western monsoon season compared to other seasons (Adriat et al., 2024). Additionally, research using the Weibull distribution in Lembasada Beach successfully predicted dominant wind speed patterns over specific periods, providing insights into the potential utilization of wind energy in coastal areas (Harianto & Karjadi, 2024; Purba, 2014). However, most of these studies have focused solely on general coastal wind analysis without considering its relationship to regional climatological variability and its implications for more specific renewable energy planning. Moreover, research on wind variability in the coastal region of West Kalimantan, particularly in Paloh District, remains limited (Suryanto et al., 2023). This study addresses this gap by analyzing long-term wind patterns and their implications for wind energy potential, which have not been extensively examined in this region.

Paloh District, located along the northern coast of West Kalimantan and directly bordering the North Natuna Sea, has unique geographical characteristics with an extensive coastline exposed to seasonal wind influences. This region is likely to experience significant wind variability throughout the year, affecting fisheries, maritime transportation, and wind energy development potential (Firdaus & Rahadian, 2018; Asyiawati & Akliyah, 2011). Wind dynamics in coastal areas such as Paloh are often influenced by global atmospheric phenomena, such as the El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD), which can enhance or reduce seasonal wind intensity (Zhou et al., 2021; Simanjuntak, 2022). ENSO, for example, is known to affect atmospheric pressure patterns in the Pacific Ocean, which subsequently influence wind intensity and direction in Southeast Asia (Huang et al., 2015). Variations in pressure and sea surface temperature in tropical regions can also lead to changes in wind patterns that impact coastal ecosystem stability and sedimentation rates along the shoreline (Fachri & Hendrayana, 2017). Therefore, this study provides a new perspective on coastal wind pattern analysis by linking wind variability to regional atmospheric factors and its implications for renewable energy.

This study aims to analyze wind speed and direction variability in the coastal region of Paloh District, West Kalimantan, based on 15 years of observational data (2009–2023). The analysis is conducted using statistical methods, including the Weibull distribution to characterize wind speed and Windrose diagrams to visualize dominant wind direction patterns (Kaplan, 2020; Pramono et al., 2022; Sirait et al., 2023). Unlike previous studies that primarily focused on seasonal or annual wind patterns, this research integrates long-term analysis with more detailed statistical modeling to identify sustainable wind variability trends. The primary advantage of this study lies in its comprehensive analysis, which links wind variability with global atmospheric phenomena (ENSO and IOD) and their impacts on coastal ecosystems and wind energy potential. Additionally, this study provides a long-term data-driven evaluation that has not been extensively conducted in the coastal region of West Kalimantan. Thus, the findings of this study are expected to offer deeper insights into wind patterns in West Kalimantan's coastal areas while serving as a foundation for coastal management and wind-based renewable energy development in Indonesia (Harianto & Karjadi, 2024; Kaplan, 2020; Purba, 2014; Zeng et al., 2019; Yunginger & Sune, 2015).

METHOD

This study employs a quantitative-descriptive approach to analyze the variability of wind speed and direction in the coastal area of Paloh District, Sambas Regency, West Kalimantan. This section systematically explains the research location, research approach, research procedures, data collection instruments, and data analysis techniques applied.

Research Location

This study was conducted in Paloh District, Sambas Regency, West Kalimantan, which directly borders the North Natuna Sea, as shown in Figure 1. This area was selected due to its unique geographical characteristics, including an extensive coastline exposed to seasonal wind influences. The atmospheric dynamics in this region are significantly affected by the monsoon system, which plays a crucial role in determining the variability of wind speed and direction throughout the year.

To support the spatial analysis in this study, a research location map was created using QGIS software, displaying administrative boundaries and the location of the BMKG Paloh meteorological station, as shown in Figure 1. This map is essential for illustrating the physical geography of the study area and its relationship with the wind dynamics being analyzed.

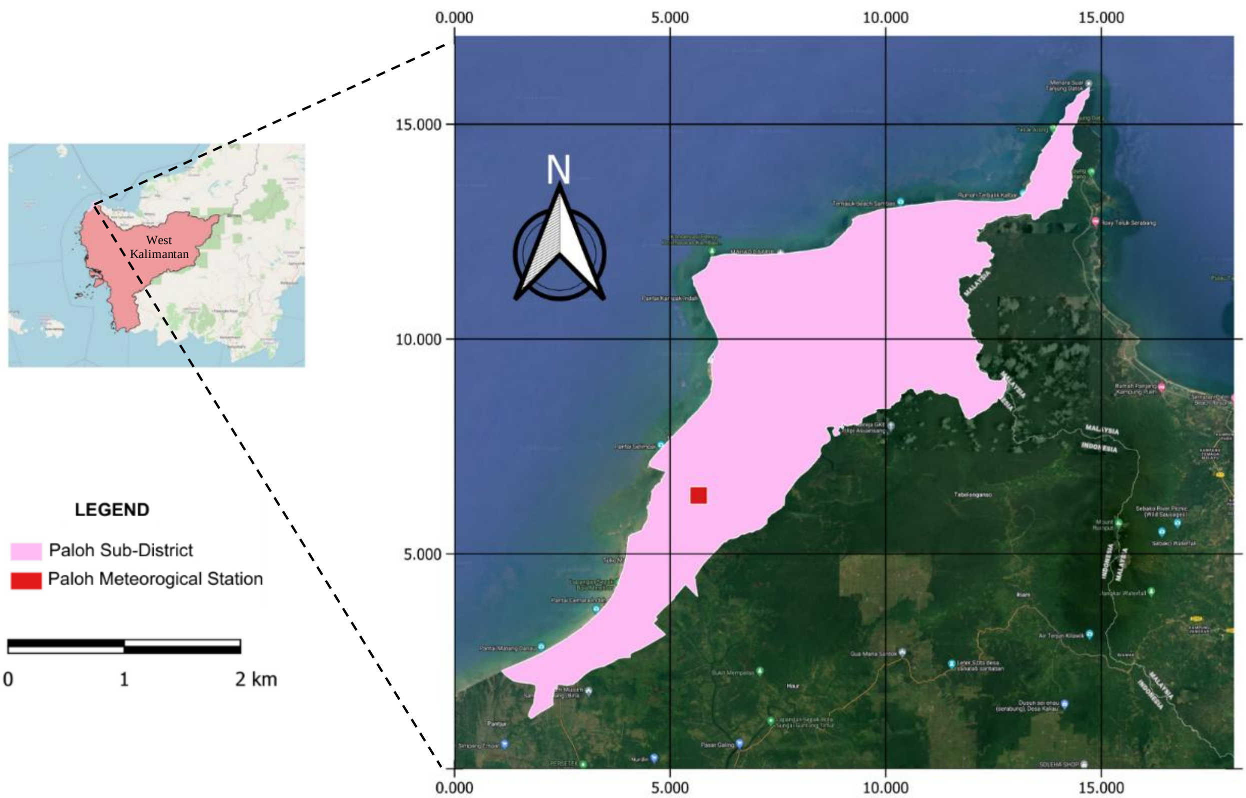

Figure 1. Study location and observational data center in Paloh District.
Source: Research Findings (2024)

Research Approach

This study employs a quantitative-descriptive approach aimed at identifying the variability of wind speed and direction through statistical analysis. The research process consists of data collection, data processing, and result analysis. The Weibull distribution is used to characterize wind speed, while the Windrose diagram is utilized to identify the dominant wind direction (Widiyanto, 2013; Bembuain, WDT., & Samaila, 2022), based on wind speed and direction data from BMKG Paloh for the period 2009–2023.

Research Procedure

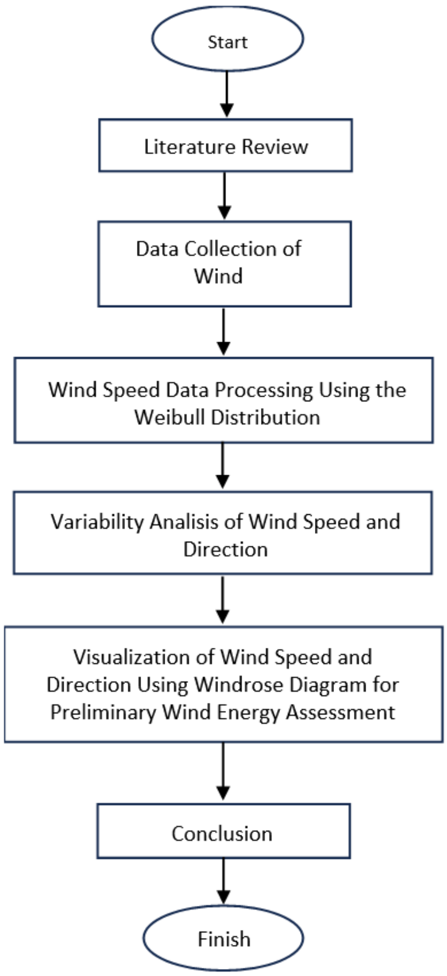

Figure 2. Research Flowchart
Source: Research Results (2024)

This research was conducted based on the flowchart shown in Figure 2. The research stages began with the collection of wind speed and direction data from BMKG Paloh for the period 2009–2023, which was used to analyze wind patterns in the study area. The obtained data were then processed using statistical methods, with the Weibull distribution applied to analyze wind speed probability.

In the Weibull function, wind speed variations are represented using the shape parameter (k) and the scale parameter (c) (Widiyanto, 2013). The Weibull function consists of the cumulative distribution function (Fw) and the probability density function (fw), which can be seen in Equations 1 and 2 below.

$$Fw = 1 - \exp\left[-\left(\frac{v}{-c}\right)^{k}\right] \quad (1)$$

$$fw = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \quad (2)$$

This study uses the Weibull distribution parameter determination with the Standard Deviation Method. This method can produce better parameter values compared to other methods (Kaplan, 2020). The calculation of parameters k and c can be seen in Equations 3, 4, 5, and 6 as follows :

$$k = \left(\frac{\sigma}{vm}\right)^{-1,086} \quad (3)$$

$$c = Vm\left(\frac{k^{2,6674}}{0,184+(0,186k^{2,73859}}\right) \quad (4)$$

$$\sigma = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(Vi - Vm)^2} \quad (5)$$

$$v_m = \frac{1}{n}\sum_{i=0}^{N} v_i \quad (6)$$

The shape parameter (k) represents wind conditions, including wind variability and stability. A k value ranging from 1.51 to 1.99 indicates a moderately windy location, whereas a k value of ≤ 1.5 signifies high wind variability or strong gusts. A k value of 2 represents moderate winds, while k ≥ 3 indicates regular and steady winds (Widiyanto, 2013). The scale parameter (c) influences the Weibull distribution curve; the smaller the c value, the more the curve shifts toward lower wind speeds.

Additionally, the Windrose diagram is used to visualize the dominant wind direction, as represented by the following equation (7):

$$\theta = tan^{-1}\left(\frac{v_u}{v_v}\right) \quad (7)$$

where θ represents the wind direction in degrees, vuv_uvu is the west-east wind speed component, and vvv_vvv is the south-north wind speed component. The wind direction analysis is conducted by considering the primary seasons in the monsoon system, namely the rainy season (DJF), the dry season (JJA), and the transitional seasons (MAM and SON). The Windrose diagram is utilized to identify changes in the dominant wind direction over time, which is crucial for assessing its impact on the coastal environment in Paloh District.

Data Collection Instrument

The data used in this study consists of wind speed and direction records from the Paloh Meteorological, Climatological, and Geophysical Agency (BMKG) for the period 2009–2023. Wind speed data was obtained directly from BMKG Paloh by submitting a formal request for data usage to analyze wind speed in Paloh District. The data was then processed using statistical methods and the Weibull distribution with the assistance of Python software. Additionally, WRPLOT View software was employed to generate Windrose diagrams, illustrating the dominant wind directions across different seasonal periods. The results from this software analysis were cross-validated using manual methods as an additional validation step to ensure the accuracy of the calculations.

Data Analysis

The data analysis techniques in this study include the Weibull distribution to determine wind speed distribution and identify the shape parameter (k) and scale parameter (c), which characterize wind conditions in the study area. The Windrose diagram was applied to analyze the dominant wind direction and observe wind pattern changes across different seasons. By employing systematic and statistical-based methods, this study aims to provide a deeper understanding of wind variability in the coastal region of Paloh District and assess its potential for wind energy development in West Kalimantan.

RESULTS AND DISCUSSION

Statistical Analysis of Monthly Wind Speed

The observational data was obtained from the BMKG Paloh Station, located at coordinates 1°44’4’’ N and 109°19’5’’ E. This dataset consists of average wind direction and speed data collected over 15 years across 12 months per year. Table 1 presents the monthly wind direction and speed data over this 15-year period, including the maximum wind speed, average wind speed, wind direction at maximum speed, and average wind direction for each month. Wind speed and direction vary from month to month. Based on this data, a monthly wind speed graph was generated, as shown in Figure 3.

Table 1. Monthly Wind Direction and Speed Data in Paloh District for the 2009–2023 Period

Month	U Max (m/s)	U Avg (m/s)	Wind Direction at Maximum Speed (°)	Average Wind Direction (°)
January	5.659	2.366	360	333
February	5.144	2.435	360	297
March	5.659	2.298	360	315
April	4.630	2.298	360	273
May	4.630	2.229	270	192
June	5.144	2.161	135	186
July	6.688	2.641	180	186
August	5.659	2.504	135	183
September	5.659	2.332	135	186
October	5.144	2.058	135	195
November	4.116	1.783	90	192
December	5.144	2.058	315	285

Source: Processed Research Data, 2024

Figure 3 illustrates the monthly wind speed trends observed over a 15-year period. The graph displays both maximum wind speed and average monthly wind speed. Based on the graph, the highest maximum and average wind speeds occur in July. This finding aligns with research by Susanto et al. (2016), which identified that wind speeds in the western Indonesian waters peak in July due to the influence of the southeast monsoon. Additionally, a study by Aldrian and Dwi Susanto (2003) indicates that seasonal wind patterns in Indonesia are influenced by the movement of the Asian and Australian monsoons, resulting in increased wind speeds during June–August (JJA) and December–February (DJF). During the transitional periods from March to May (MAM) and September to November (SON), wind speeds tend to decrease. This phenomenon is attributed to shifts in wind direction and intensity due to the movement of the Intertropical Convergence Zone (ITCZ). These findings are further supported by Qian (2008), who noted that ITCZ shifts influence rainfall distribution and wind patterns in Indonesia's maritime region.

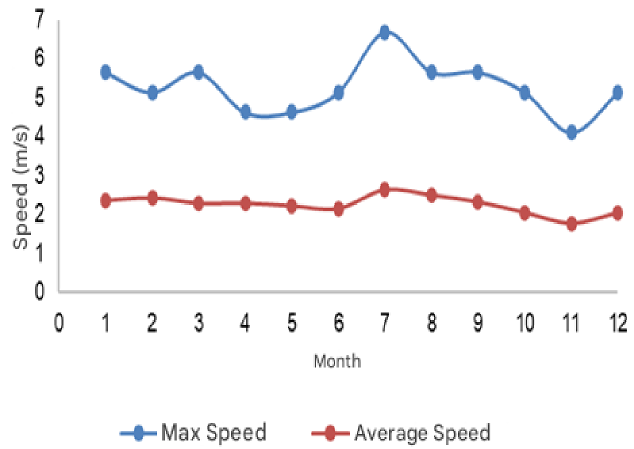

Figure 3. Monthly Wind Speed Patterns Based on BMKG Paloh Observational Data
Source: Research Findings (2024)

In accordance with monsoonal wind patterns, wind speeds increase during June, July, and August (JJA) and December, January, and February (DJF) (Haiyqal et al., 2023). Conversely, during the transition periods in March, April, and May (MAM) and September, October, and November (SON), wind speeds tend to decrease. This decline during MAM and SON is attributed to changes in the direction and intensity of dominant zonal and meridional winds in a given region (Simanjuntak, 2022).

Statistical Analysis of Annual Wind Speed

In addition to monthly wind direction and speed data, this study also examines annual wind direction and speed data, as shown in Table 2. Table 2 presents annual wind direction and speed, derived by aggregating data from 12 months of each year. The table includes maximum wind speed, average wind speed, wind direction at maximum speed, and average wind direction. Wind speed and direction vary from year to year. Based on this data, an annual wind speed graph has been generated, as illustrated in Figure 4.

Table 2. Annual Wind Direction and Speed Data in Paloh District (2009–2023)

Year	U Max (m/s)	U Avg (m/s)	Wind Direction at Maximum Speed (°)	Average Wind Direction (°)
2009	2,058	1,500	360	360
2010	1,543	1,243	360	258,75
2011	1,543	1,115	360	266,25
2012	1,029	1,029	360	262,5
2013	2,058	1,415	360	247,5
2014	2,058	1,372	360	266,55
2015	1,543	1,029	180	255
2016	1,543	1,072	315	236,25
2017	4,630	3,172	135	225
2018	3,601	2,658	360	225
2019	5,659	4,673	360	228,75
2020	5,144	3,944	360	191,25
2021	2,572	2,101	360	168,75
2022	4,630	3,730	315	153,75
2023	6,688	3,901	180	183,75

Source: Processed Research Data (2024)

Figure 4 illustrates annual wind speed fluctuations, with an increase from 2016 to 2017, a subsequent decline, another rise in 2019, followed by a decrease until 2021, and an increase in 2022 and 2023. A study by Zeng et al. (2019) suggests that global land wind speed trends exhibit irregular patterns, primarily driven by large-scale ocean-atmosphere circulation variability caused by long-term climate change. These fluctuations in wind speed may also be linked to phenomena such as El Niño-Southern Oscillation (ENSO). Research by Hendon (2003) indicates that during El Niño phases, wind patterns across Indonesia shift, influencing both wind speed and direction.

Additionally, a study by McVicar et al. (2012) highlights that land-use changes and urbanization can impact regional wind speed patterns, potentially contributing to the observed fluctuations in Paloh District.

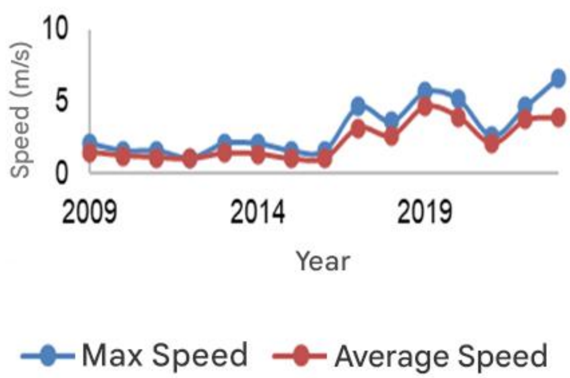

Figure 4. Annual Wind Speed Patterns Based on BMKG Paloh Observational Data
Source: Research Findings (2024)

Moreover, the study conducted by Zeng et al. (2019) shows that the trend of land wind speed globally is uncertain and has an irregular pattern. This is caused by long-term climate change related to the annual variability of large-scale ocean-atmosphere circulation. The causes of wind speed changes remain a complex debate, but the main suspected cause of wind speed shifts is changes in circulation patterns due to uneven warming in various regions (Zhou et al., 2021). Uneven surface warming of the Earth (temperature anomalies or heterogeneity) affects the oscillation of ocean-atmosphere climate indices and pressure gradients. The greater the air pressure gradient, the greater the pressure difference between two places, and the stronger the wind that blows (Fernando, 2021). Annual wind speed has an irregular pattern; when wind speed decreases, it will increase in the following years and oscillate irregularly (Zeng et al., 2019).

Weibull Distribution of Wind Speed in Paloh

Based on the calculation of the Weibull distribution parameter values using the Standard Deviation Method (STDM), the shape parameter (k) was obtained at 2.260 and the scale parameter (c) at 3.525. The shape parameter (k) is the main indicator in describing the characteristics of wind speed distribution at a specific location (Wijaya, 2023). In general, a value of $k \leq 1.5$ indicates that the wind in the area has high variability with significant fluctuations, while a value of $k = 2$ reflects more stable and moderate wind conditions (Widiyanto, 2013). With $k = 2.260$, it can be concluded that the wind speed in Paloh District has a fairly good level of stability, although it still experiences variations due to seasonal factors and global atmospheric phenomena. Additionally, a k value greater than 2 indicates a relatively stable wind speed distribution, which is consistent with the findings of Seguro and Lambert (2000) that a k value between 2 and 3 reflects moderate and stable wind conditions. The study by Amrani et al. (2023) also supports the use of the Weibull distribution in analyzing wind energy potential, with a similar k value indicating suitability for wind energy development.

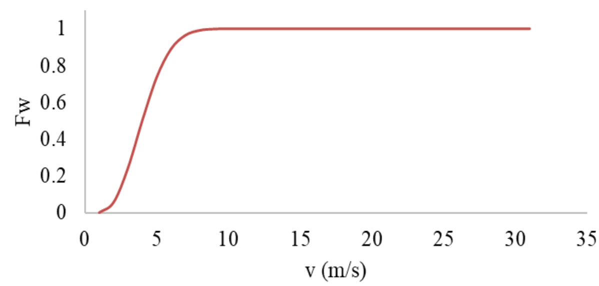

Figure 5. Cumulative Weibull Distribution Graph (Fw) for Wind Speed in Paloh District During the Period 2009–2023.
Source: Research Findings (2024).

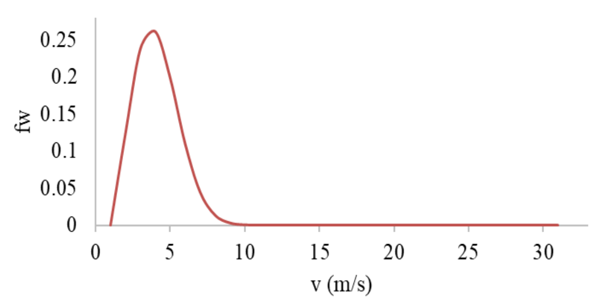

Figure 6. Weibull Probability Graph (Fw) for Wind Speed in Paloh District During the Period 2009–2023.
Source: Research Findings (2024).

Weibull Distribution is used to understand the probability of wind speed reaching a certain value over an observed period. Figure 5 shows the Weibull cumulative distribution function (Fw), which illustrates the cumulative probability of wind speed being less than or equal to a reference speed at the study location. The xaxis represents wind speed in m/s, while the y-axis shows the cumulative probability (Fw). In this graph, the Fw value rises sharply, approaching 1 at around 10 m/s, indicating that most wind speeds at the study site do not exceed this value. This suggests that the probability of low wind speeds is higher than high wind speeds, an important indicator in wind energy utilization planning (Fachri & Hendrayana, 2017).

In addition to the cumulative distribution, Figure 6 presents the Weibull probability function (fW), which describes the relative probability of wind speed in Paloh District. The peak of the curve in this graph is around 5 m/s, meaning that this wind speed occurs most frequently compared to other speeds. After reaching its peak, the probability declines sharply, indicating that higher wind speeds have a lower likelihood of occurrence. These findings are consistent with previous research showing that areas with $k > 2$ have relatively stable wind distribution patterns, with dominant wind speeds within an optimal range for wind energy conversion (Kaplan, 2020; Zhou et al., 2021). This result also aligns with studies by Akdağ and Dinler (2009), who found that the dominant wind speed in several locations in Turkey was around 5 m/s, indicating sufficient potential for small-scale wind power generation.

The Weibull distribution has been widely used in wind energy research to identify wind speed patterns and assess the feasibility of an area for wind resource utilization (Ajayi, 2010). Several studies have shown that areas with k values between 2 and 3 generally have sufficient wind potential for economic electricity generation (Gugliani et al., 2024; Wais, 2016). Additionally, Zhou et al. (2021) found that a Weibull distribution with k above 2.0 provides accurate estimations of wind energy potential in coastal areas. Therefore, with $k = 2.260$ obtained in this study, Paloh District has good prospects for local-scale wind energy development.

The Weibull distribution analysis in this study provides a deeper understanding of wind speed variability in the coastal region of West Kalimantan, specifically in Paloh District, Sambas Regency. Combining the cumulative distribution function and probability function enables a more comprehensive mapping of wind energy potential. Figure 6 is more representative in showing the most frequently occurring wind speeds. However, for a more thorough understanding of wind speed patterns in Paloh District, Figures 4 and 5 should also be included to provide a more accurate depiction of wind characteristics in the study area.

Windrose Analysis of Wind Direction in Paloh

Wind direction data over 15 years (2009–2023) was visualized using the WRPLOT application and categorized into eight main directions. This visualization includes both monthly and annual diagrams. The monthly windrose diagram (Figure 7) shows that from January to April, winds predominantly blow from the North; in May and June from the Southeast; in July from the South; in August from the Southeast; in September from the Southeast and South; in October from the East and West; in November from the East; and in December from the Northwest. This variation aligns with research by Aldrian and Dwi Susanto (2003), which states that wind patterns in Indonesia are influenced by the movement of the Asian and Australian monsoons, causing wind direction changes according to the seasons.

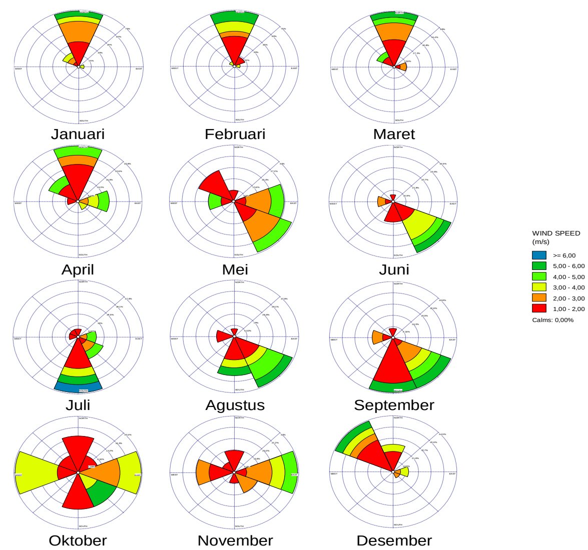

Figure 7. Windrose diagram of monthly wind speed in Paloh Subdistrict during the period 2009–2023. *Source: Research Findings (2024)*

The variation in wind direction illustrated in Figure 7 is a result of seasonal changes driven by monsoons. Seasonal transitions influence wind direction due to fluctuations in air pressure and temperature (Lubis & Yosi, 2012). With each monsoonal shift, wind patterns tend to reverse and blow in opposite directions (Akhsan, 2021). During the period from June to September, the Asia-Australia monsoon blows from the southeast (originating from the Australian continent) toward the northwest (toward the Asian continent), and is known as the Southeast Monsoon. Conversely, during the December to March period, the wind direction reverses, blowing from the northwest to the southeast (Webster, 2020). As shown in Figure 7, during transitional (inter-monsoonal) seasons, wind directions tend to be irregular, occurring in March, April, and May (MAM), as well as in September, October, and November (SON). At the peak of the dry season—June, July, and August (JJA)—the dominant wind direction is from the south and southeast. In contrast, during the peak of the rainy season—December, January, and February (DJF)—the prevailing winds blow from the northwest and north. Subsequently, an annual wind direction visualization is presented in Figure 8.

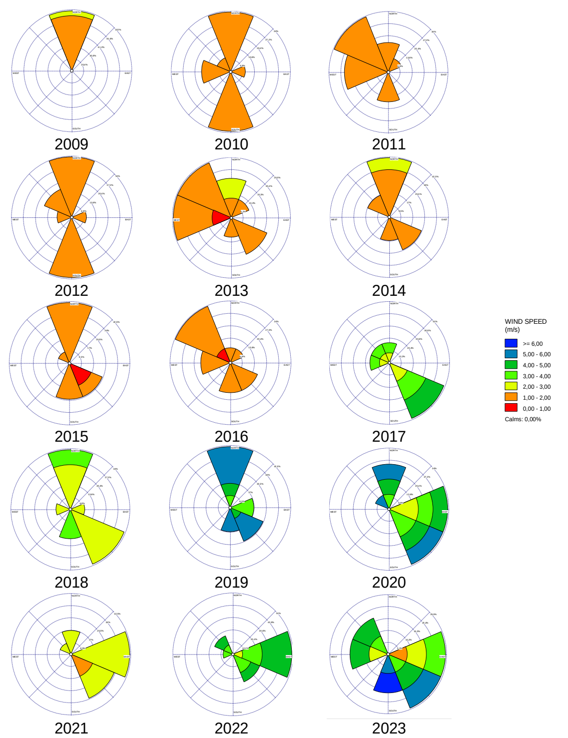

Figure 8. Annual windrose diagram of wind speed in Paloh Subdistrict during the period 2009–2023.
Source: Research Findings (2024)

Figure 8 presents an annual diagram spanning 15 years, from 2009 to 2023. This annual windrose diagram illustrates the variation in dominant wind directions each year, which may be influenced by global climatic phenomena such as ENSO. A study by Chang et al. (2005) indicated that ENSO affects rainfall and wind patterns in the Indonesian maritime region, which may explain the observed variations in annual wind directions in Paloh Subdistrict. Dominant wind directions vary depending on the temporal scale—daily, monthly, seasonal, or annual. Interannual variability may occur due to changes in atmospheric pressure patterns, temperature gradients, and other climatic factors (Ganske et al., 2016). The force generated by differences in atmospheric pressure gradients drives air movement from high-pressure areas to low-pressure areas; the greater the pressure gradient, the stronger the wind speed. Temperature gradients also influence wind speed—larger temperature gradients result in greater pressure differences, prompting changes in wind direction and altitude (Seidel et al., 2020). Additionally, annual dominant wind directions are influenced by other factors such as monsoonal wind patterns, atmospheric pressure, and seasonal changes (Haryanto et al., 2020).

CONCLUSION

Based on the conducted research, the conclusions drawn are as follows: according to the calculation of the Weibull distribution parameters using the Standard Deviation Method (STDM), the shape parameter (k) was found to be 2.260, and the scale parameter (c) was 3.525. Based on the Weibull distribution, the most frequent wind speed observed at the study location was 5 m/s. The highest monthly maximum and average wind speeds occurred in July. In accordance with the monsoonal pattern, wind speeds increased during June, July, and August (JJA), as well as in December. During the transitional periods—March, April, and May (MAM), and September, October, and November (SON)—wind speeds tended to decrease. The annual wind speed pattern appears irregular due to uneven surface heating (temperature anomalies or heterogeneity), which influences the oscillation of ocean-atmosphere climate indices and pressure gradients.

The dominant monthly wind direction during the transitional (inter-monsoonal) seasons tends to be irregular, as seen in March, April, and May (MAM), and September, October, and November (SON). At the peak of the dry season, namely in June, July, and August (JJA), the dominant winds blow from the south and southeast. Conversely, at the peak of the rainy season—December, January, and February (DJF)—the prevailing winds blow from the northwest and north. The dominant annual wind direction is influenced by changes in atmospheric pressure patterns, temperature gradients, and other climatic factors. The stronger the atmospheric pressure gradient, the faster the wind blows. Likewise, a larger temperature gradient results in greater pressure differences, which cause the wind to change direction and altitude.

For future research, several improvements can be made to enhance the accuracy and relevance of the results. One key approach is to expand the data sources by combining reanalysis data from ECMWF ERA-5 with higher-resolution numerical models such as the Weather Research and Forecasting (WRF) model, which can capture wind variability in greater detail at the local scale. Additionally, long-term variability analysis should be considered, particularly to examine the impacts of global climate phenomena such as the El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) on wind speed and direction patterns. Understanding how climate change affects wind characteristics on an interannual basis would provide deeper insights into fluctuations that may influence the future potential of wind energy.

Furthermore, validation of the current research findings can be strengthened by incorporating direct observational data from meteorological stations or lidar-based monitoring technologies. These methods would allow for more accurate calibration of the Weibull distribution under real field conditions. Future studies on wind speed and direction patterns can also be developed in the context of renewable energy utilization, especially for identifying optimal locations for wind farm development. A more integrated analysis, combined with technical studies on wind turbine design and efficiency, would significantly contribute to supporting the transition to clean and sustainable energy. With more comprehensive follow-up studies, it is expected that the understanding of wind dynamics in the study area will be enhanced, serving as a scientific foundation for optimizing wind energy development in Indonesia.

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Conflict of Interest: The authors declare that there are no competing interests relevant to the content of this article.

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