*Bangladesh Journal of Physics, Vol. **33**, Issue 1, pp. 51 – 66, June 2026*

STATISTICAL ESTIMATION OF WIND POWER DENSITY FOR RENEWABLE ENERGY APPLICATIONS IN DINAJPUR DISTRICT, BANGLADESH

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Received on 18.06.2026, Revised received on 24.06.2026, Accepted for publication on 30.06.2026

DOI: ***https://doi.org/10.3329/bjphy.v33i1.90957***

ABSTRACT

Statistical approaches were employed to assess wind energy of Dinajpur, northern Bangladesh, using monthly average wind speed data collected from 2019 to 2023. The wind energy potential of the region was assessed by analyzing its wind characteristics and power density using the Weibull (WB) and Rayleigh (RL) distributions. The results indicate that wind speeds (WS) reach their maximum values during April, whereas the lowest speeds are observed in October. The values of k varies from 2.329 to 3.5, whereas the values of c ranges from 2.923 m/s and 3.125 m/s. Both statistical models show distribution pattern of wind speed satisfactorily; however, Weibull distribution provides slightly superior fit to the observed data. In contrast, the Rayleigh model yields comparatively smaller errors in wind power density (WPD) estimation. Considerable yearly variation in WPD is also observed over the five-year study period, with the highest potential occurring in 2022. The outcomes of the study improve understanding of wind characteristics in Dinajpur and may assist in future wind energy planning and turbine deployment in northern Bangladesh.

Keywords: Wind speed; Weibull distribution; Scale parameter; Rayleigh distribution; Shape factor.

1. INTRODUCTION

The growing worldwide demand for clean and sustainable energy solutions has highlighted the importance of renewable resources [1, 2]. Evaluation of advanced technologies [3] reveals that wind, solar, hybrid wind with solar, cooling/solar heating, and energy systems of biomass are practical options for developing countries. Among these options, wind energy is widely regarded as an environmentally friendly and sustainable energy source that contributes to minimizing greenhouse gas emissions and enhancing energy security [4]. Assessment of wind resource availability with high accuracy is essential for feasibility studies of wind energy developments. Exact estimation of the wind characteristics helps to identify the appropriate locations for the installation of wind farm and improves efficiency and consistency of power generation systems. Furthermore, proper wind resource assessment minimizes investment risks, optimizes turbine selection, and supports long term energy planning and policy formulation [5, 6]. Statistical approaches of wind data have therefore become an important approach for evaluating wind resource potential in different geographical regions. Among the numerous statistical approaches, Weibull (WB) and Rayleigh (RL) distribution models are broadly used due to their effectiveness in unfolding wind speed (WS) frequency distributions and also estimating power density of wind with reasonable accuracy.

Several probability density functions (PDF) have been studied extensively to characterize wind speed frequency distributions [7-16]. Among the available statistical approaches, WB is currently the most widely employed and recognized statistical approach for addressing wind energy and other renewable energy applications [17-22]. The widespread use of the WB distribution can be attributed to its ability to provide an accurate fit to observed WS data and its reliance on only two parameters, as highlighted by Tuller and Brett [23]. To estimate the wind power density (WPD) and the possibility of wind resources, the WB PDF's shape and scale parameter play crucial roles. The RL distribution is obtained from the WB distribution under specific value of shape parameter [7]. Because of the simplicity and practical applicability, Corotis et al. [24] also implemented RL distribution to describe WS. Owing to their ability to estimate wind characteristics and energy production from limited meteorological data, these statistical models are widely used for the preliminary assessment of wind power (WP) potential. Furthermore, WB and RL statistical models enable comparative evaluations of wind patterns in different regions and support the optimization of wind energy harvesting systems to improve power generation efficiency.

In the context of Bangladesh, multiple studies have assessed wind energy potential across coastal belts and particular inland sites [25-35]. However, studies focusing on long-term wind trends and wind resource potential in Dinajpur and the northern region of Bangladesh remain limited. Since Dinajpur is well known for its agro-based industries, the demand for energy has shown an increasing trend in the region. Therefore, this study presents an analysis of measured WS data obtained at 10 m above the ground during the period from 2019 to 2023 [36] for Dinajpur (25.6221° N, 88.6438° E), Bangladesh. Understanding regional wind characteristics is essential for accurate assessment of wind energy resources, site-specific energy planning, and development of sustainable renewable energy policies. In addition, reliable evaluation of local wind regimes can support the selection of suitable wind energy conversion systems and contribute to reducing requirement on conventional fossil-fuel-based energy sources [37, 38]. This study aims to assess the statistical significance of WS data from Dinajpur, Bangladesh, for predicting wind energy generation and facilitating rational decision making.

2. THEORETICAL ANALYSES

2.1 Distributions of wind speed (WS)

The representation of wind characteristics through probability density distributions and their corresponding functional forms has become a fundamental aspect of wind energy literature. These probability distributions have broad applications in wind energy research, including the estimation of distribution function parameters, WS data analysis, and techno-economic evaluation of wind energy systems. The WB distribution, commonly employed to characterize wind speed, is generally expressed as follows [39-41]:

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

where $f(v)$ represents PDF of WS (v), c is the WB scale parameter (with the unit m/s), and k is the dimensionless WB shape parameter.

The Cumulative probability density function (CDF) that based on WB distribution is expressed as [42-44]:

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

The WB becomes equivalent to the RL if the value of k is set to 2. Therefore, Equation 1 reduces to the RL distribution when $k = 2$ [8, 45]:

$$f(v) = \left(\frac{2v}{c^2}\right) \exp\left[\left(-\frac{v}{c}\right)^{2}\right] \tag{3}$$

Here v_a is the mean value and σ is the standard deviation (SD) associated with the WB distribution are calculated as [20, 46]:

$$v_a = c\Gamma\left(1 + \frac{1}{k}\right) \tag{4}$$

$$\sigma = c\left[\Gamma\left(1 + \frac{2}{k}\right) - \Gamma^2\left(1 + \frac{1}{k}\right)\right]^{0.5} \tag{5}$$

Where Γ () is the gamma function.

2.1.1 Standard deviation (SD) method

The following formulas are applied to estimate parameters of the WB distribution [47, 48]:

$$k = \left(\frac{\sigma}{v_a}\right)^{-1.086} \tag{6}$$

$$c = \frac{v_a}{\Gamma(1+\frac{1}{k})} \tag{7}$$

2.2 Two meaningful wind speeds

After obtaining the WB parameters (k *and* c) for wind distribution across the selected location, the most probable WS (v_{MP}) and the WS carrying the maximum energy (v_{MaxE}) can also be easily estimated [49]. These two WSs are especially significant for wind resource assessors. The first corresponds to the maximum point of the PDF, while the latter is used as a basis for estimating turbine design parameters [50]. Both parameters are evaluated using the following equations [20, 51, 52]:

$$v_{MP} = c\left(\frac{k-1}{k}\right)^{1/k} \tag{8}$$

$$v_{MaxE} = c\left(\frac{k+2}{k}\right)^{1/k} \tag{9}$$

where, k and c represents the WB parameters. For optimal wind turbine design, the two estimated terms should be closely associated [53].

2.3 Wind power density

The equation below expresses the WP through the blade sweep area (A), indicating that it increases proportionally to the cube of the velocity [16, 42-44, 54-56]:

$$P(v) = \frac{1}{2}\rho A v^3 \tag{10}$$

where ρ refers to the mean air density, which is 1.225 kgm^{-3} under standard atmospheric conditions regarding temperature 15°C. The WPD depends on several parameters, including altitude, air pressure, and temperature.

The WB PDF is used to compute expected WPD per unit area for monthly as follows [44]:

$$P_w = \frac{1}{2}\rho c^3 \Gamma\left(1+\frac{3}{k}\right) \tag{11}$$

Here, c represents the WB scale parameter.

When $k = 2$, equation (7), RL PDF is expressed as [44]:

$$P_R = \frac{3}{\pi}\rho {v_a}^3 \tag{12}$$

$P_{m,\ R}$ denotes the WPD estimated from the actual WS probability distribution and is regarded as the reference mean power density. It can be determined using the following equation [44, 46]:

$$P_{m,\ R} = \sum_{j=1}^{n}\left[\frac{1}{2}\rho {v_m}^3 f(v_j)\right] \tag{13}$$

The percentage error between the WPDs estimated using the probability distributions and the reference values derived from the measured WS probability distribution can be calculated using the following equation [44, 57]:

$$\text{Error}\ (\%) = \frac{\mathrm{P_{w,\ R}} - \mathrm{P_{m,\ R}}}{\mathrm{P_{m,\ R}}} \tag{14}$$

Where $\mathrm{P_{w,\ R}}$ represents the average power density.

2.4 Statistical assessment of distributions

The WB and RL PDF are evaluated using the coefficient (R^2) of determination, and root mean (RMSE) square error [58]. These parameters are evaluated using expressions given below [54]:

$$R^2 = \frac{\sum_{i=1}^{N}(y_i - z_i)^2 - \sum_{i=1}^{N}(x_i - y_i)^2}{\sum_{i=1}^{N}(y_i - z_i)^2} \quad (15)$$

$$\text{RMSE} = \left[\frac{1}{\text{N}} \sum_{i=1}^{N}(y_i - x_i)^2\right]^{1/2} \quad (16)$$

Where y_i, z_i, x_i, and N stand for the ith measured value, the mean, the predicted value from WB or RL distributions, and the total number of observations, respectively [59]. The distribution providing the best fit is identified through maximum R^2 and minimum RMSE.

3. WIND SPEED DATA

The Bangladesh Meteorological Department (BMD) serves as the primary source of meteorological and WS data in Bangladesh [36]. In the study, hourly wind data recorded at a height of 10 m for Dinajpur (25.6221° N, 88.6438° E), Bangladesh, covering the period from 2019 to 2023, were utilized for the analysis. The wind measurements were obtained using generator-type anemometer, which is widely used for reliable monitoring of wind speed in meteorological observations. Collected dataset was analyzed to evaluate wind characteristics and estimate the wind potential of the study area using WB and RL statistical models.

3.1 Wind speed (WS) variation with hub height

The present analysis is based on WS data measured at a standard reference height of 10 m above ground level, while most commercial wind turbines have greater hub heights. WS near the Earth's surface varies with height, requiring the use of an appropriate wind profile equation to estimate WS at a desired height from measurements obtained at a reference height. The power law is the widely used approach for estimating the variation of WS at different hub height and is expressed as follows [54, 55]:

$$\frac{v_1}{v_2} = \left(\frac{h_1}{h_2}\right)^{\alpha} \quad (17)$$

Where, v_1, and v_2 denote the mean WSs measured at the heights h_1, and h_2. The value of 'α' depends on numerous aspects as atmospheric stability and the roughness of surface. The numerical value of α generally lies between 0.05–0.50, with 0.14 commonly assumed for terrains exhibiting low surface roughness and minimal obstructions [56, 60].

4. RESULTS AND DISCUSSIONS

In the present work, a comprehensive analysis of WS data recorded in Dinajpur, Bangladesh has been conducted. Subsequently, the WB k and c parameters, together with the monthly mean WS and mean WP, were calculated. The key results of this study are presented as follows:

Table 1 presents the monthly mean WSs and SDs derived from the collected data for the entire study period and for each of the five individual years. The majority of v_a values lie within the range of 2.0-3.0 m/s, whereas some fall between 3.0 and 4.0 m/s, and only a few are less than 2.0 m/s. Across the entire study period, the highest value of v_a (4.028 m/s) was recorded in April 2022, whereas the lowest value of 1.722 m/s occurred in October 2020. The annual mean WS remained relatively consistent, ranging from 2.611 to 2.792 m/s. The SD values for both annual and monthly WSs are mostly within the range of 1.0-2.0 m/s, with only a few values below 1.0 m/s. In comparison with

Dinajpur, Rangpur experiences its highest WSs during June and July, whereas the smallest values are found in October and November [27]. Although both locations are within the same climatic region, differences in the observation period, sensor height, local exposure, surface roughness, and interannual monsoon variability may account for the observed differences in seasonal wind characteristics. For the years of 2019 to 2023, the variations of v_a are presented in Fig. 1. It is observed that the pattern of v_a remains largely consistent among the five years.

Table 1 Monthly WS Characteristics: mean WS v_a and SD (σ) for Dinajpur, Bangladesh.

Years	2019		2020		2021		2022		2023		Entire year	
Variable	v_a	σ	v_a	σ	v_a	σ	v_a	σ	v_a	σ	v_a	σ
January	2.333	1.028	2.306	1.083	2	0.839	2.389	0.703	2.25	0.747	2.256	0.88
February	2.556	1.278	2.361	0.972	2.278	0.794	2.667	0.997	2.472	0.908	2.467	0.99
March	2.806	2.083	2.667	1.639	2.611	1.747	2.778	0.975	2.861	1.836	2.744	1.656
April	3.194	1.472	2.889	1.694	3.139	1.181	4.028	0.997	2.833	1.497	3.217	1.368
May	3.972	1.278	3.639	1.389	3.25	1.111	3.417	1.067	3.083	1.339	3.472	1.237
June	3.389	1.306	3.194	1.306	3.444	1.019	3.556	0.931	3.778	1.203	3.472	1.153
July	3.389	1.472	2.972	1.167	3.222	0.931	2.889	0.861	3.167	0.883	3.128	1.063
August	3.194	1.278	3.472	1.111	2.667	0.794	2.917	1.089	2.75	1.133	3.000	1.081
September	2.75	1.167	2.75	1.139	2.417	0.931	2.75	0.772	2.944	1.044	2.722	1.011
October	1.75	0.972	1.722	0.944	2.028	0.747	2.167	0.931	2.222	0.839	1.978	0.887
November	1.75	0.917	2.139	1.111	1.833	0.567	1.889	0.567	2.083	0.772	1.939	0.787
December	2.139	1	1.889	0.889	2.444	0.681	2.056	0.681	2.056	0.725	2.117	0.795
Yearly	2.769	1.271	2.667	1.204	2.611	0.945	2.792	0.881	2.708	1.077	2.709	1.076

The monthly PDF and corresponding CDF obtained from the time-series data of Dinajpur are displayed in Figs. 2 and 3, respectively. The results indicate that all the PDF and CDF curves exhibit nearly identical trends with respect to WS. The annual PDF together with the corresponding CDF is illustrated in Fig. 4. During the pre-monsoon and early monsoon (April-June), the wind speed is maximum in this area because the elevated surface heating intensifies the pressure gradient and also increase the instability of the atmosphere. Conversely, WSs decline because of stable atmospheric conditions during October–November.

The yearly values of WB parameters, c (m/s) and k (dimensionless) derived from the wind data of Dinajpur are summarized in Table 2. The parameters c and k were derived based on the methodology presented in Section 2.1.1. Over the study period (2019–2023), the yearly values of k varied from 2.329 to 3.500, averaging 2.727. The annual c varied from a minimum of 2.923 m/s in 2021 to a maximum of 3.125 m/s in 2019. The estimated mean value of c is 3.046 m/s during the analysis period. The monthly k varied between 1.382 and 4.554, whereas the value of c ranged from 1.941 to 4.420 m/s. In comparison, a previous study carried out in Rangpur [27] found the WB shape parameter to range from 1.893 to 3.289, while the scale parameter varied from 6.547 to 20.211 m/s. Hasan et al. [35] estimated the Weibull parameters using different methods for four different regions of Bangladesh, and the obtained values are considerably higher than those reported in the present study. Another recent study by Ahmed et al. [33] estimated the Weibull parameters using different estimation methods for eleven different regions of Bangladesh, and the obtained values are consistent with those reported for Dinajpur. The observed variations in these parameters reflect moderate fluctuations in wind characteristics and are useful for evaluating the WP potential and turbine efficiency in Dinajpur.

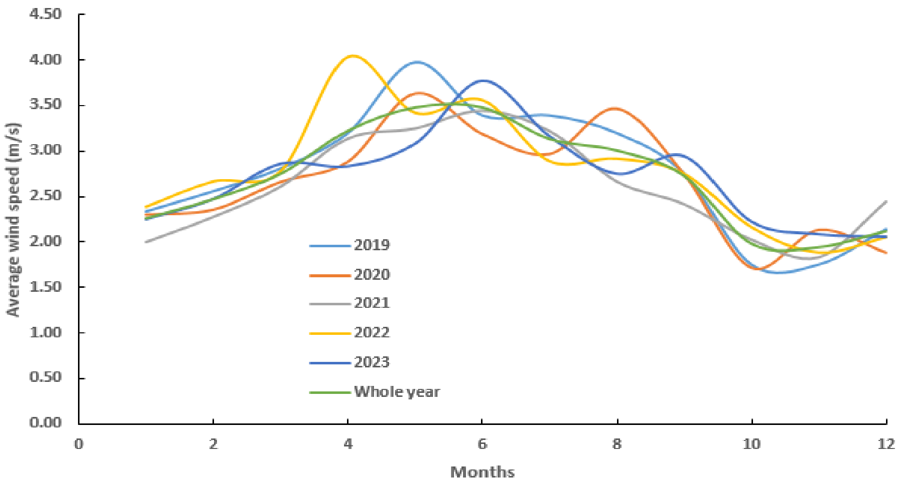

Fig 1. Variation of monthly mean WS in Dinajpur between 2019 and 2023.

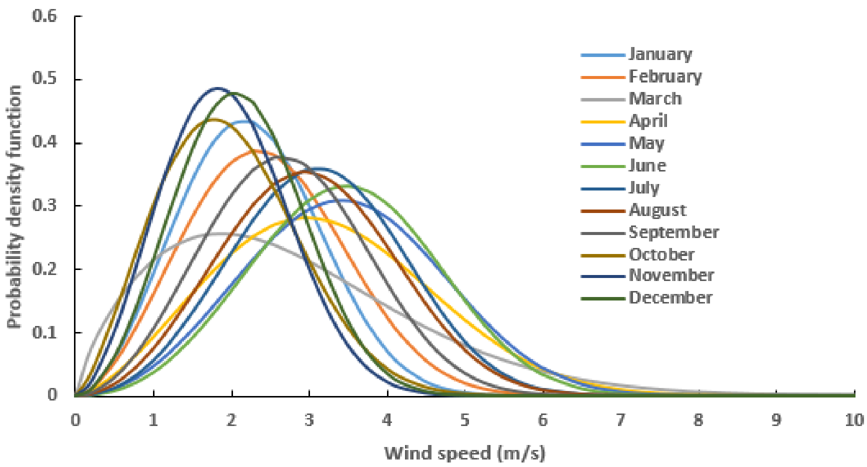

Fig 2. Monthly WSs PDF relied on time series data from Dinajpur.

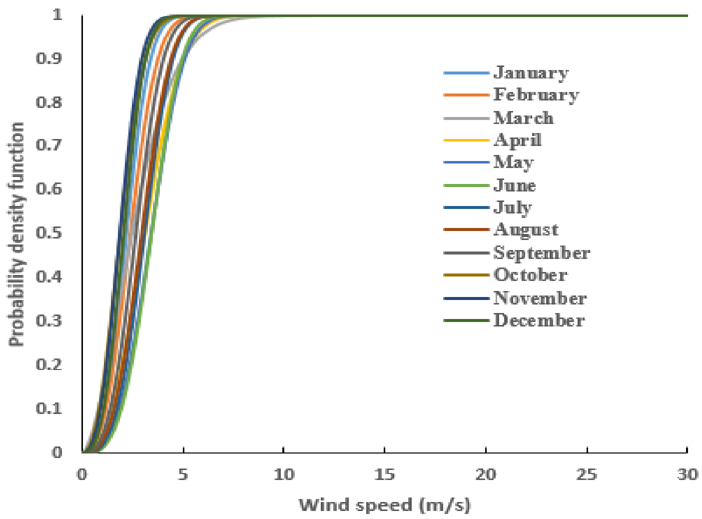

Fig 3. Monthly WSs CDF obtained from the measured data over the entire year of Dinajpur.

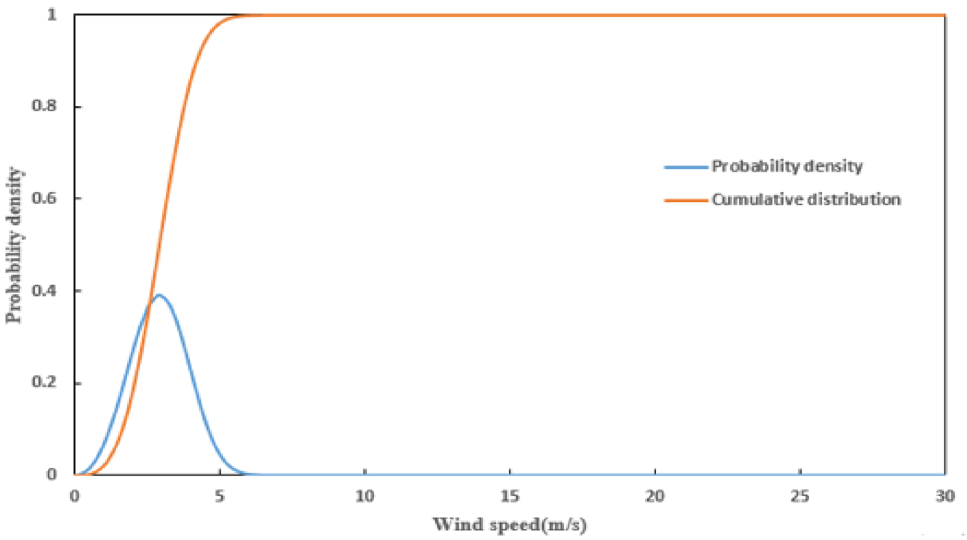

Fig 4. Yearly WS PDF and CDF estimated from the observed data for entire year of Dinajpur.

Table 2 Monthly k and c regarding Dinajpur with respect to 2019-2023.

Period	2019		2020		2021		2022		2023		Entire year	
Variable	c	k	c	k	c	k	c	k	c	k	$\boldsymbol{c}$	$\boldsymbol{k}$
Jan	2.631	2.436	2.603	2.271	2.252	2.569	2.644	3.776	2.508	3.311	2.534	2.779
Feb	2.886	2.123	2.658	2.621	2.545	3.139	2.99	2.91	2.77	2.966	2.774	2.695
March	3.072	1.382	2.988	1.697	2.903	1.547	3.105	3.117	3.195	1.619	3.079	1.731
April	3.605	2.319	3.247	1.785	3.521	2.892	4.411	4.554	3.197	1.999	3.624	2.53
May	4.42	3.427	4.084	2.846	3.628	3.208	3.795	3.54	3.476	2.474	3.884	3.068
June	3.805	2.818	3.595	2.643	3.814	3.752	3.907	4.288	4.201	3.466	3.87	3.312
July	3.82	2.473	3.34	2.761	3.562	3.853	3.2	3.723	3.494	4.001	3.491	3.229
August	3.592	2.705	3.862	3.447	2.954	3.725	3.27	2.915	3.095	2.619	3.358	3.029
September	3.098	2.538	3.096	2.605	2.713	2.819	3.035	3.972	3.293	3.082	3.051	2.933
October	1.972	1.893	1.941	1.92	2.272	2.957	2.442	2.504	2.493	2.881	2.231	2.39
November	1.975	2.018	2.414	2.037	2.035	3.579	2.093	3.697	2.335	2.938	2.181	2.664
December	2.415	2.283	2.132	2.267	2.697	4.009	2.291	3.322	2.298	3.101	2.374	2.896
Yearly	3.125	2.329	3.009	2.372	2.923	3.015	3.103	3.5	3.045	2.721	3.046	2.727

The measured WS probability distribution, together with its WB and RL approximations, is presented in Fig. 5, and their comparative performance with the observed distribution is provided in Table 3. It is evident from Fig. 5 that the WB distribution provides a better fit to the actual data than the RL distribution. The results presented in Table 3 show that the WB distribution achieved the highest R^2 value. However, the WB distribution exhibits lower RMSE value compared with the RL distribution.

Table 4 presents the WPD (P), annual mean WS, and annual WB parameters. The estimated parameters vary slightly from year to year during the 2019–2023 period, but significant fluctuations are observed in WPD. These fluctuations highlight the influence of year-to-year changes in meteorological conditions on the available wind energy resource. It can also be observed that the highest WPD (26.561 W/m²) was obtained in 2022, which is associated with the relatively higher mean wind speed during that year. Fig. 6 compares the WPDs obtained from the measured probability density distribution with those estimated using the WB and RL distributions. Significant monthly variations in WPD are observed. According to Fig. 6, lower WPDs are observed in January, February, October, November, and December, while significantly higher values occur in April, May, and June. For the remaining months, the WPDs are intermediate between the lowest and highest values. The WB approximation predicts lower WPDs compare to RL distribution.

Figure 7 summarizes the errors in power density estimation for the distribution models with respect to the measured distribution. For the WB model, the maximum error is recorded in March, while the minimum error occurs in November. The RL distribution also displays the highest error in March. Overall, the RL distribution performs better in calculating the mean error values power density than the WB distribution in Dinajpur.

Table 3 Annual comparison of measured, WB, and RL wind speed distributions.

f(v)			
Wind speed	Actual data	WB	RL
1.0	0.105	0.125	0.166
2.0	0.298	0.315	0.285
3.0	0.358	0.334	0.297
4.0	0.181	0.175	0.208
5.0	0.038	0.0441	0.108
6.0	0.0034	0.00501	0.041
7.0	0.00012985	0.00023	0.011
8.0	2.06489E-06	4.24333E-06	0.002
9.0	1.38334E-08	2.65888E-08	0.0003
10	3.9043E-11	5.33885E-11	0
11	4.64232E-14	3.1557E-14	0
12	2.32544E-17	5.05084E-18	0
R^2		0.993	0.945
RMSE		0.0104	0.031

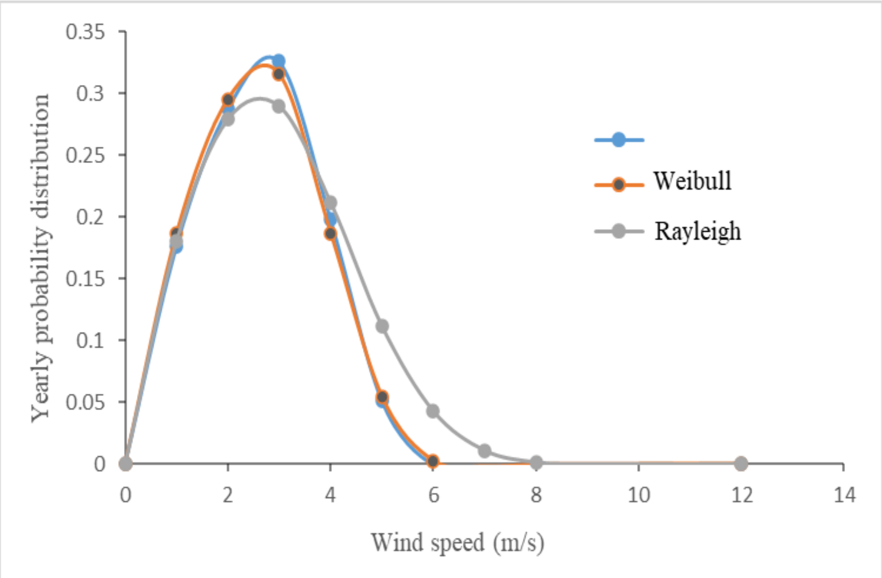

Fig 5. Measured WS probability distribution and its WB and RL approximations.

Table 4 Annual wind speed trends for Dinajpur between 2019 and 2023.

Year	v_a (ms^{-1})	k	c (ms^{-1})	v_{MP} (ms^{-1})	v_{MaxE} (ms^{-1})	P (Wm^{-2})
2019	2.77	2.33	3.12	2.456	4.077	21.641
2020	2.67	2.37	3.01	2.388	3.893	19.062
2021	2.61	3.01	2.92	2.558	3.461	15.271
2022	2.79	2.92	3.50	3.033	4.183	26.561
2023	2.71	3.10	2.72	2.400	3.194	12.177

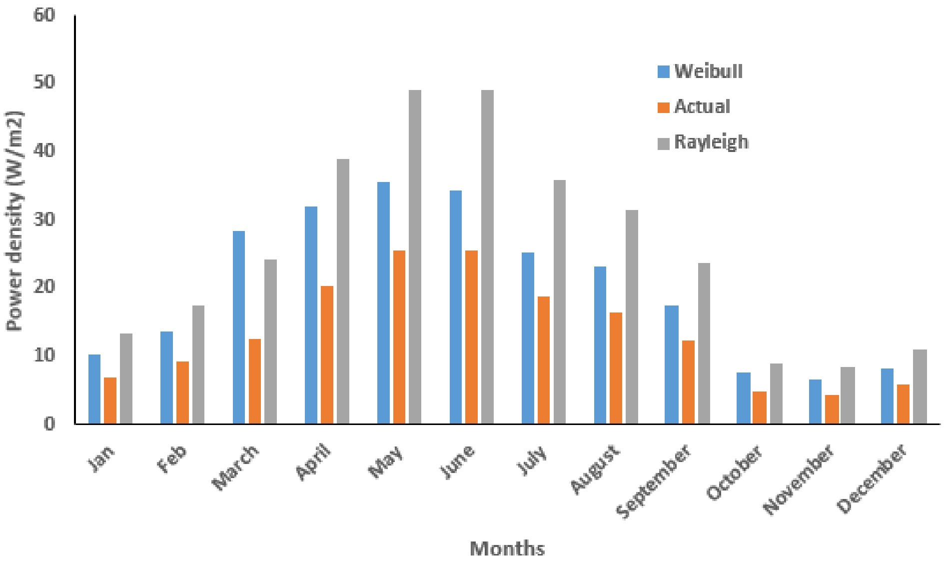

Fig 6. Monthly comparison of measured and modeled WPD.

4.1 WS regarding hub-height

In this study, a power-law exponent of 0.14 was adopted, as Dinajpur is predominantly characterized by agricultural land and relatively low surface roughness. The wind shear analysis was calculated using Eq. (18) at 10 m, 30 m, 50 m, and 80 m. The velocity of wind increases with increasing height above the ground, rising from 2.709 m s^{-1} at 10 m to 3.16, 3.39, and 3.62 m s^{-1} at 30 m, 50 m, and 80 m, respectively. Although increasing trend, the WS values still remain low for large commercial wind turbines. Therefore, hybrid or small-capacity wind turbines, such as the NPS 100C-24, may be considered for evaluating the feasibility of community-scale wind energy applications in the study area [33].

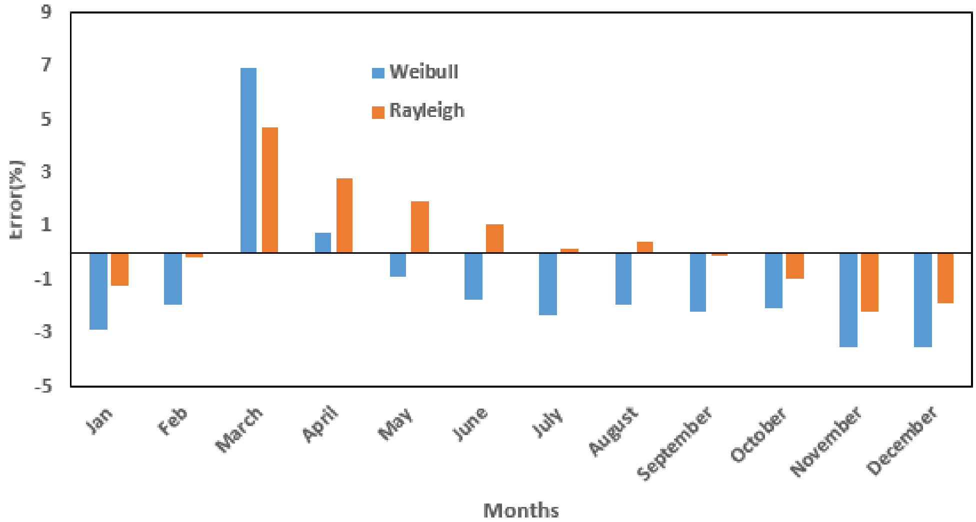

Fig 7. Monthly WPD errors were evaluated using WB and RL models.

5. CONCLUSIONS

This study evaluates WP of Dinajpur, situated in northern region of Bangladesh, using five years (2019–2023) of monthly mean WS data measured at a height of 10 m and collected from the BMD. The wind characteristics were analyzed using two-parameter WB and RL statistical distribution models. The results reveal that highest monthly mean WSs observed in April, whereas the lowest value was recorded in October, indicating noticeable seasonal variations in wind behavior.

The estimated annual WB shape parameter (k) ranges from 2.329 to 3.5, whereas scale parameter (c) varies between 2.923 and 3.125. Both WB and RL distributions demonstrate good agreement with perceived wind data; however, WB model provides a slightly superior fit, as confirmed by higher R^2 and lower RMSE. The WPD analysis demonstrates that the study area exhibits interannual variability, highlighting the importance of long-term observations for reliable wind resource assessment and wind energy planning. In addition, the error analysis indicates that the RL model generally yields lower mean errors in estimating WPD, suggesting its suitability for preliminary wind resource assessments in the study area. The results suggest that the relatively low wind speeds in the study area are more suitable for small-scale wind turbines than for large commercial wind farms. These findings contribute to better understanding of wind regime characteristics of Dinajpur and provide useful information for future wind resource assessment, turbine site selection, and renewable energy planning in Bangladesh. The outcomes of this research may also support policymakers and energy planners in promoting sustainable and clean energy development in the northern region of the country. Future research should incorporate long-term measurements, techno-economic analyses, and site suitability assessments to identify the most appropriate locations for wind energy development.

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