Indonesian Journal of Earth Sciences, Vol. 04, No. 1 (2024), A1037

P-ISSN: 2798-1134 | E-ISSN: 2797-3549 | DOI: 10.52562/injoes.2024.1037

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Indonesian Journal of Earth Sciences

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Investigation of Seasonal and Annual Wind Speed Distribution of Tarnab Based on Weibull and Rayleigh Distribution Models

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Received: 13 May 2024 / Accepted: 13 June 2024 / Published: 18 June 2024

Abstract: This study aims to statistically analyze wind speed data of Tarnab, Peshawar, for the period 2004-2023. The data was recorded at the Agriculture Research Institute, Tarnab, Peshawar. Two statistical models (two-parameter Weibull and Rayleigh distribution functions) were applied to find the distributions of wind speeds. For the estimation of shape and scale parameters of Weibull and Rayleigh, two methods were employed: the method of moments and the energy pattern factor. Three statistical tools (mean percentage error, mean absolute percentage error, and root mean square deviation) were applied to check the error percentage of both models. The results of the Weibull distribution were much closer to the observed data than those of the Rayleigh distribution. The average values of wind speeds tended to increase from winter to summer and vice versa. The highest recorded annual and seasonal wind speeds were 26.19 in/s and 41.57 in/s, respectively, while the lowest values were 7.11 in/s and 4.95 in/s, respectively. Thus, while ruling out the possibility of harnessing wind as a significant source of energy, the findings are still useful for the crops produced in the region.

Keywords: Wind speed, Weibull distribution, Rayleigh distribution, shape factor, scale factor

INTRODUCTION

An important way to understand a region's potential for agriculture and renewable energy is through statistical modeling of its wind speed changes. Tarnab, a town located in the suburbs of Peshawar, is mostly agricultural land. According to the Climate Data Processing Center (CDPC) of Pakistan, the mean monthly temperature of Peshawar in the summer can rise above 40 °C and may be as low as 27 °C, while in the winter, the mean maximum is 18.35 °C and the mean minimum is 4 °C. The region lies in the low rainfall range, receiving less than 600 mm of rainfall annually (Manzoor et al., 2020). According to limited and relevant studies, such as those by Khatri et al. (2022) and Ali et al. (2023), Tarnab lies in wind power class 2 with a wind speed of 0-5.4 m/s (or 0-212.59 inches/s) and mean values of wind speed less than 3.5 m/s (137.7 inches/s) at a height of 100 m (Saeed et al., 2021). However, there is quite a rich literature related to wind speed analysis for other parts of Pakistan (e.g., Adnan et al., 2021; Hulio, 2021; Khan et al., 2022; Ahmad et al., 2023) and many more, which will be discussed shortly in the next paragraph along with similar studies conducted in other parts of the world. While research on climate variability has historically focused on air temperature and rainfall, recent decades have seen an increased interest in near-surface wind speed features (Ikbal et al., 2022; Jung & Schindler, 2019). Numerous statistical distributions have been employed to analyze wind speeds, with the Weibull distribution emerging as the most prevalent due to its adaptability and simplicity (Koroglu & Ekici, 2024). Previous studies, such as those by Wang et al. (2018) and Guarienti et al. (2020), have demonstrated the effectiveness of the Weibull model in various contexts, emphasizing its broad applicability.

Sarkar et al. (2017), in performing different statistical distributions for various locations in India, concluded that small wind speed values are best interpreted by the Weibull model and larger by the extreme value distribution. However, intermediate spans of wind speeds are not well reported by the Weibull model. For the cities located along the coastal line of Balochistan, a study concluded that the Weibull distribution is a better fit than Rayleigh (Azhar et al., 2019). Wind power analysis via the Weibull distribution for various locations in Sindh province pinpointed crucial sites (having wind power class from fair to marginal) for making use of wind as an energy resource (Tahir et al., 2021). Sumair et al. (2021) performed wind speed analysis along the coastal line of Pakistan at several sites, declaring Weibull to be the best fit and the Rayleigh model the worst fit to the actual data. In a study, Suwarno & Zambak (2021) showed that the ordinary 2-parameter Weibull distribution produces better results than the modified Weibull distribution for wind speeds greater than 2 m/s and vice versa. However, the properties of the PDF are alike. Jalal & Ali (2022) compared the Weibull and Rayleigh probability density functions (PDF) for Turbat, Balochistan, showing the Weibull PDF to be a better fit to the observed data than Rayleigh. Hussain et al. (2023) studied the Weibull models of four port cities located along the coastal line of Balochistan to find potential candidates for wind power generation. The exponential Weibull (EW) is shown to outperform the two- and three-parameter Weibull (W2 and W3) respectively for the wind speed distribution at Poprad airport, located at 718 m above sea level. The EW distribution has also been found suitable for cases where the majority of the data lies on the left side of the graph (Pobočíková et al., 2023). In a comparative case between W2 and W3, the latter has been found to show better performance in Mthatha, South Africa, over a period of ten years. However, both distributions fit quite well with the data of the South African weather service (Shonhiwa et al., 2023).

Despite the widespread use of the Weibull distribution, there is a need for more precise models that can accurately estimate wind speed distributions, particularly in regions with complex climatic conditions like Tarnab. Existing studies have predominantly focused on large-scale wind speed patterns, leaving a gap in the understanding of seasonal and annual variations at local scales. This study aims to fill this gap by providing a detailed analysis of wind speed distributions in Tarnab over a 20-year period, using both Weibull and Rayleigh models.

This study aims to address the challenge of accurately modeling seasonal and annual wind speed variations in Tarnab, a town with a hot semi-arid climate near Peshawar, over a 20-year period (2004-2023). The research problem centers on identifying the most suitable statistical models for wind speed distribution and understanding their implications for agricultural planning and renewable energy potential. The objectives of this study are: (1) to analyze the seasonal and annual wind speed variations in Tarnab from 2004 to 2023; (2) to compare the effectiveness of Weibull and Rayleigh distribution models in representing wind speed data; (3) to estimate the shape and scale parameters using the method of moments (MOM) and energy pattern factor (EPF); and (4) to evaluate the practical implications of wind speed distributions for agricultural planning and renewable energy potential in the region.

METHOD

Wind speed data from the past 20 years (i.e., from 2004 to 2023) taken on a daily basis is employed in this study. The data is recorded at the Agriculture Research Institute (ARI) Tarnab, located 16 km away from the center of Peshawar (Lat: 34.011244° N, Long: 71.705972° E, elevation 309 m). The mean maximum and minimum temperatures recorded at ARI Tarnab during the study period are 29.41 °C and 13.74 °C, respectively. The annual rainfall for the period is less than 600 mm except for the years 2010, 2015, and 2018, during which annual rainfall of more than 600 mm was observed. The data is recorded by a mechanical counter anemometer mounted on a pillar (calibrated in km/h with an accuracy of 0.5 km/h) at a height of 2.032 m from the surface. Although the device is not based on modern electronic or digital technology, it is maintained properly for accuracy and functionality twice a year. The data is recorded in units of inch/s because m/s values of speed are too low to be compared with the distributions. It should be noted that the wind speed data was taken once a day at 8 AM every morning, resulting in 1807, 1839, 1840, and 1820 data points for the DJF, MAM, JJA, and SON seasons, respectively. The combined annual data points for the 20 years are 7306. Additionally, the study lacks spatial distribution. Furthermore, the weather at the mentioned site comprises four seasons during the year: Dec-Feb (DJF, winter); Mar-May (MAM, spring); Jun-Aug (JJA, summer); and Sep-Nov (SON, autumn). Finally, the current work will focus solely on wind speed since the site lacks the facility to calculate wind direction.

Weibull and Rayleigh Distribution Models

Originally theorized by physicist Waloddi Weibull, the Weibull distribution (Rajput et al., 2022) is a statistical distribution with numerous applications in meteorological studies and software applications (such as Wind Atlas Analysis and Application Program, WasP) based on its mathematical framework (Younis et al., 2023). Other distributions for modeling wind speed may also be utilized, but the Weibull distribution has the edge over them as it can model both right- and left-skewed wind speeds, which other models fall short of (Rajput et al., 2022).

The probability density function (PDF) (Deep et al., 2020) and cumulative distribution function (CDF) of a two-parameter Weibull distribution are given by the following equations:

$$f_w(u) = \frac{k}{\lambda}\left(\frac{u}{\lambda}\right)^{k-1} e^{-\left(\frac{u}{\lambda}\right)^k} \tag{1}$$

$$F_w(u) = 1 - e^{-\left(\frac{u}{\lambda}\right)^k} \tag{2}$$

where k is a dimensionless quantity defined as the shape factor, λ in units of speed is the scale factor and u is the wind speed. Together these two factors k and λ describe the characteristics of a Weibull curve. The Rayleigh model is actually a special case of the Weibull model with a fixed shape parameter of 2 (i.e., $k = 2$). The PDF of a Rayleigh distribution is the same as equation 1 except for $k = 2$, hence:

$$f_R(u) = \frac{2u}{\lambda^2} e^{-\left(\frac{u}{\lambda}\right)^2} \tag{3}$$

For the selection of shape and scale parameters, there are numerous methods reported in the literature (Akgül et al., 2016; Shoaib et al., 2019; Malik et al., 2021), such as the graphical method (GM), method of moments (MOM), maximum likelihood method (MLM), modified maximum likelihood method (MMLM), energy pattern factor (EPF), and standard deviation method (STDM). It is this choice of parameter selection in the Weibull distribution that enables it to estimate several data distributions in addition to wind speed distributions.

For the purpose of this work, two methods (MOM and EPF) for parameter estimation are selected since both are found to be not only elementary but also methodical. MOM is usually known for its evaluation of mean, standard deviation, asymmetry, and tailedness of the wind speed distribution (Hussain et al., 2023), whereas EPF requires the least computation of all (Wadi & Elmasry, 2021) along with its superior level of precision when the shape factor lies in the range 1.2 to 2.75 (Akdag & Guller, 2015).

MOM uses average wind speed ($\bar{u}_i$) and standard deviation (σ) as moments for further estimating the shape k and λ parameters. Moments $\bar{u}_i$ and σ are calculated directly from the wind speed data using excel. Hence, the shape (k) and scale (λ) are given by Guarienti et al. (2020) the following equations:

$$k = \left(\frac{0.9874}{\frac{\sigma}{\bar{u}_i}}\right)^{1.0983} \tag{4}$$

$$\lambda = \frac{\bar{u}}{\Gamma\left(1+\frac{1}{k}\right)} \tag{5}$$

Now, the EPF (Hasan et al., 2022) is defined by the ratio of the average of cube of wind speed to the cube of the average:

$$E_{pf} = \frac{\overline{u^3}}{(\bar{u})^3} = \frac{\Gamma(1+{}^3/_k)}{\Gamma^3(1+{}^1/_k)} \tag{6}$$

where

$$\bar{u} = \lambda\Gamma(1+\frac{1}{k}) \tag{7}$$

the shape factor is then given by:

$$k = 1 + \frac{3.69}{E_{pf}^2} \tag{8}$$

and for the scale factor, the previous equation 5 of MOM is employed. The goodness of fit of MOM and EPM techniques will be tested by three types of statistical errors discussed in the following subsection.

Useful Wind Speeds

The most frequently occurring wind speed, also known as the most probable (MP) wind speed, and the maximum energy (ME) carrying wind speed (Saeed et al., 2020), can be obtained from the values of k and λ as follows:

$$u_{mp} = \lambda\left(1 - \frac{1}{k}\right)^{1/k} \tag{9}$$

$$u_{\max E} = \lambda\left(1+\frac{2}{k}\right)^{1/k} \quad (10)$$

Similarly, using the same parameters, we may acquire the average values predicted by the Weibull and Rayleigh distributions (Parajuli, 2016) as follows:

$$\bar{u}_w = \lambda\Gamma\left(1+\frac{1}{k}\right) \quad (11)$$

$$\bar{u}_R = \lambda\left(\frac{\pi}{4}\right)^{1/2} \quad (12)$$

where $\bar{u}_w$ and $\bar{u}_R$ denote the average speeds for the Weibull and Rayleigh distributions, respectively. The next section is dedicated to the discussion of crucial results obtained by the techniques mentioned in this section.

Statistical Errors

To analyze how well the observed data fits with the Weibull and Rayleigh distributions obtained by both MOM and EPM, the types of statistical error calculating tools used are: mean percentage error (MPE), mean absolute percentage error (MAPE), and root mean square deviation (RMSD).

$$MPE = \frac{1}{N}\sum_{i=1}^{n}\left(\frac{u_{i(w,R)}-u_{i,m}}{u_{i,m}}\right)\times 100\% \quad (13)$$

$$MAPE = \frac{1}{N}\sum_{i=1}^{n}\left|\frac{u_{i(w,R)}-u_{i,m}}{u_{i,m}}\right|\times 100\% \quad (14)$$

$$RMSD = \left[\frac{1}{N}\sum_{i=1}^{n}\left(u_{i,m}-u_{i(w,R)}\right)^2\right]^{1/2} \quad (15)$$

where $u_{i(w,R)}$ is the ith weibull or Rayleigh frequency, $u_{i,m}$ is the frequency of ith observed data, N gives the number of class intervals or bins.

In relation to large statistical data, there are often some crucial terms connected to the distributions. The next section will shed light on those terms for the wind speed.

RESULTS & DISCUSSION

Annual Wind Speed Analysis

We are studying near-surface wind speeds at the height, $h \approx 80$ inches (2.032 m) from the surface. Before delving into the seasonal statistical evaluation of wind speed, first a presentation the annual statistical analysis of wind speed of Tarnab has been carried out. The values of k, λ ($k = 2$, fixed for Rayleigh distribution) and other parameters are presented for each year for the both MOM and EPF techniques in Table 1. For MOM, k ranges from 1.66 to 9.26, while for EPF, the range of k is limited to 1.64 to 4.37. The value of λ ranges from 7.95 in/s to 29.40 in/s for MOM and from 7.97 in/s to 29.43 in/s for EPF. The MP speeds (u_{mp}) for Weibull are generally greater than those of Rayleigh model due to its dependency on the shape of distribution greatly.

Table 1. Annual Weibull and Rayleigh parameters

Year	Method of Moments (MOM)							
	Weibull					Rayleigh		
	k	λ	u_{mp}	$u_{max\ E}$	$\bar{u}_w$	u_{mp}	$u_{max\ E}$	$\bar{u}_R$
2004	2.34	29.12	22.94	37.92	25.8	20.59	41.18	25.8
2005	2.46	28.79	23.31	36.65	25.54	20.36	40.72	25.51
2006	2.81	29.4	25.14	35.6	26.19	20.79	41.58	26.05
2007	2.23	20.57	15.76	27.41	18.22	14.55	29.1	18.23
2008	2.81	19.17	16.39	23.2	17.07	13.55	27.1	16.98
2009	2.84	17	14.6	20.51	15.15	12.02	24.05	15.07
2010	2.77	16.51	14.06	20.08	14.7	11.68	23.35	14.63
2011	3.13	7.95	7.03	9.31	7.11	5.62	11.25	7.05
2012	4.69	8.88	8.43	9.57	8.12	6.28	12.55	7.86

Year	Method of Moments (MOM)							
	Weibull					Rayleigh		
	k	λ	u_{mp}	$u_{max\ E}$	$\bar{u}_w$	u_{mp}	$u_{max\ E}$	$\bar{u}_R$
2013	4.7	10.55	10.03	11.38	9.65	7.46	14.92	9.35
2014	7.64	9.98	9.79	10.28	9.37	7.05	14.11	8.84
2015	9.26	10.22	10.09	10.44	9.69	7.23	14.45	9.06
2016	1.66	10.6	6.06	17.11	9.48	7.5	14.99	9.39
2017	2.78	29.11	24.8	35.38	25.92	20.59	41.17	25.8
2018	2.76	29.04	24.67	35.39	25.85	20.54	41.07	25.73
2019	2.32	24.34	19.09	31.82	21.57	17.21	34.42	21.57
2020	1.97	20.75	14.51	29.58	18.4	14.67	29.35	18.39
2021	1.8	17.11	10.89	25.95	15.22	12.1	24.2	15.16
2022	2.15	23.8	17.81	32.29	21.08	16.83	33.66	21.09
2023	1.88	19.63	13.11	28.86	17.43	13.88	27.76	17.39
Avg	3.25	19.13	15.43	24.44	17.08	13.53	27.05	16.95
Year	Energy Pattern Factor (EPF)							
	Weibull					Rayleigh		
	k	λ	u_{mp}	$u_{max\ E}$	$\bar{u}_w$	u_{mp}	$u_{max\ E}$	$\bar{u}_R$
2004	2.48	29.08	23.63	36.9	25.8	20.57	41.13	25.77
2005	2.51	28.78	23.5	36.36	25.54	20.35	40.7	25.5
2006	2.76	29.43	24.99	35.86	26.19	20.81	41.61	26.07
2007	2.41	20.55	16.45	26.42	18.22	14.53	29.07	18.21
2008	2.91	19.14	16.57	22.9	17.07	13.53	27.07	16.96
2009	2.83	17.01	14.57	20.56	15.15	12.03	24.05	15.07
2010	2.91	16.48	14.26	19.74	14.7	11.66	23.31	14.6
2011	2.96	7.97	6.94	9.49	7.11	5.64	11.27	7.06
2012	3.63	9.01	8.24	10.16	8.12	6.37	12.74	7.98
2013	3.76	10.69	9.85	11.97	9.65	7.56	15.12	9.47
2014	4.26	10.3	9.68	11.28	9.37	7.29	14.57	9.13
2015	4.37	10.64	10.02	11.59	9.69	7.52	15.04	9.42
2016	1.64	10.6	5.97	17.22	9.48	7.49	14.98	9.39
2017	2.85	29.09	24.98	35.07	25.92	20.57	41.14	25.77
2018	2.9	28.98	25.05	34.73	25.85	20.5	40.99	25.68
2019	2.56	24.29	20.03	30.41	21.57	17.18	34.35	21.52
2020	2.18	20.77	15.68	27.99	18.4	14.69	29.38	18.4
2021	1.96	17.17	11.95	24.55	15.22	12.14	24.28	15.21
2022	2.27	23.8	18.45	31.4	21.08	16.83	33.65	21.08
2023	2.02	19.67	14.04	27.63	17.43	13.91	27.81	17.43
Avg	2.81	19.17	15.74	24.11	17.08	13.56	27.11	16.99

The ME carrying speeds ($u_{\max E}$) for both MOM and EPF by Weibull are smaller than those of the Rayleigh model since these speeds depends on the scale of distribution. The average speeds predicted by Weibull model ($\bar{u}_w$) for both MOM and EPF are greater than those predicted by Rayleigh ($\bar{u}_R$). Table 2 represent the error percentages for both models and both methods of parameter estimation. The values of all percent errors for MOM are smaller than those for EPF except RMSD, meaning MOM yields values much closer to the actual than EPF. Likewise, the Weibull values are smaller than those of Rayleigh, making the Weibull more in line with the actual data of wind speed data of Tarnab than the Rayleigh distribution.

Table 2. Percent errors and RMSD values of annual Weibull and Rayleigh for MOM and EPF

Method	Weibull			Rayleigh		
	MPE %	MAPE %	RMSD	MPE %	MAPE %	RMSD
MOM	6.21	35.58	0.0070	-42.33	60.61	0.0076
EPF	8.29	36.64	0.0071	-42.48	60.67	0.0076

Seasonal wind speed analysis

Table 3 shows the seasonal variation of wind speeds throughout the period 2004-2023.

Table 3. Average seasonal wind speeds for all the years from 2004-2023

Year	DJF (Winter)	MAM (Spring)	JJA (Summer)	SON (Autumn)	Annual Average
2004	17.83	24.32	41.47	19.58	25.80
2005	17.01	26.54	40.59	18.02	25.54
2006	19.62	30.05	38.53	16.55	26.19
2007	12.34	21.45	28.32	10.78	18.22
2008	16.39	21.87	20.68	9.34	17.07
2009	11.70	15.21	23.16	10.52	15.15
2010	9.71	18.85	17.15	13.09	14.70
2011	9.15	6.21	8.17	4.93	7.11
2012	7.08	10.37	8.79	6.36	8.12
2013	8.13	10.68	12.00	7.80	9.65
2014	9.07	9.95	9.92	8.55	9.37
2015	9.33	10.90	10.33	8.20	9.69
2016	5.78	7.96	7.75	16.42	9.48
2017	18.71	29.68	38.52	16.76	25.92
2018	15.77	32.43	33.24	21.95	25.85
2019	18.93	27.62	29.05	10.66	21.57
2020	14.98	28.83	23.18	6.60	18.40
2021	7.32	25.05	20.55	7.95	15.22
2022	16.10	24.67	26.45	17.10	21.08
2023	8.45	18.38	30.84	12.03	17.43
Seasonal Average	12.66	20.05	23.43	12.16	--------

According to Table 3 and Figure 1, wind speeds tend to increase as the season changes from cold to hot, with a minimum to maximum value of 4.95 in/s in Autumn 2011 to 41.57 in/s in Summer 2004. Moreover, a general decreasing trend is evident until 2011; after that, no significant increase in speeds was observed until 2017. The same trend is also mimicked by the annual average wind speed. For the annual mean values, the maximum speed is observed as 26.19 in/s while the minimum was 7.11 in/s in 2006 and 2011, respectively.

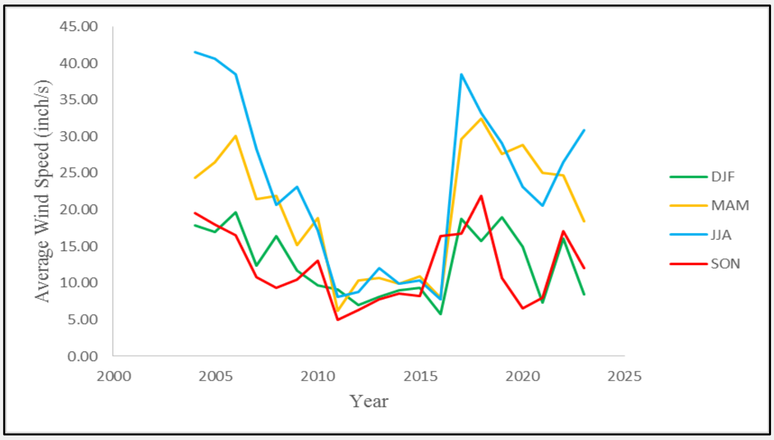

Figure 1. Average wind speed values from 2004-2023 of the seasons DJF (green), MAM (orange), JJA (blue), and SON (red).

All the parameters such as $\bar{u}, \sigma, \kappa$ and λ for all the seasons were calculated by both MOM and EPF techniques (Table 4). The average seasonal speeds exhibit the same increasing pattern of Table 3 as the summer season arrives and then decline towards the Autumn. The shape factor (k) for MOM lies in the range 1.26 to 1.49. For EPF, the range is 1.23 to 1.49, which is claimed to be the suitable range of k values for using EPF method (Akdag & Guller, 2015). The maximum and minimum values of scale factor (λ) for MOM and EPF are (25.93, 13.09) in/s and (26.34, 12.99) in/s, respectively.

Table 4. Seasonal shape and scale parameters

Method	Season	$\bar{u}$ (in/s)	σ	k	λ (in/s)
MOM	Winter	12.66	9.78	1.31	13.73
	Spring	20.05	13.77	1.49	22.19
	Summer	23.43	16.15	1.48	25.93
	Autumn	12.16	9.70	1.26	13.09
EPF	Winter	12.66	9.78	1.23	13.31
	Spring	20.05	13.77	1.40	21.97
	Summer	23.43	16.15	1.49	26.34
	Autumn	12.16	9.70	1.23	12.99

Figure 2 shows the PDF obtained by Weibull and Rayleigh by both the MOM and EPF techniques for the Winter season (DJF). The PDF of Weibull obtained by EPF (green dotted curve) and MOM (red dashed curve) fits the heavy-tailed curve (solid blue line/observed data) better than the PDF of Rayleigh by EPF (orange dotted curve) and MOM (black dashed curve). In Figure 3, the Weibull (red dashed for MOM and green dotted for EPF) curves exhibit better fitting with the observed data (blue curve) in Spring (MAM) in comparison to the Rayleigh (black dashed for MOM and orange dotted for EPF). But unlike the DJF season (Figure 2), the Rayleigh for MAM (Figure 3) is much closer to each other.

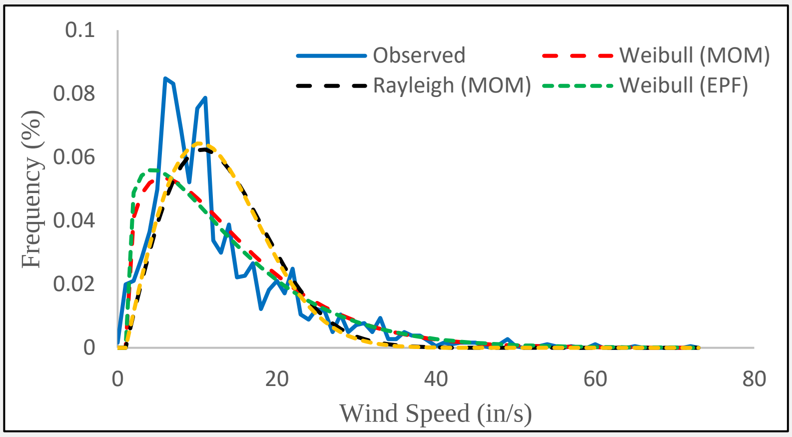

Figure 1. Wind speed distribution vs. % Frequency of Winter for Weibull PDF by MOM (Red dashed), EPF (Green dotted), Rayleigh by MOM (Black dashed), EPF (Orange dotted), and the observed data (Blue solid line).

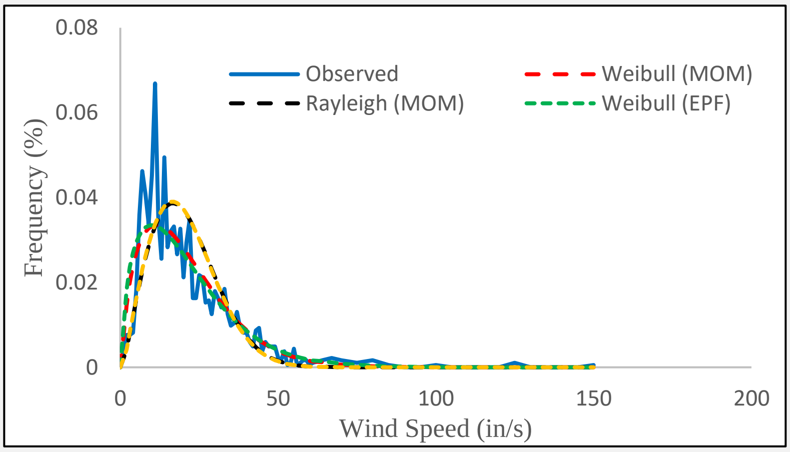

Figure 2. Wind speed profile against % Frequency of Spring for Weibull PDF by MOM (Red dashed), EPF (Green dotted), Rayleigh by MOM (Black dashed), EPF (Orange dotted), and the observed data (Blue).

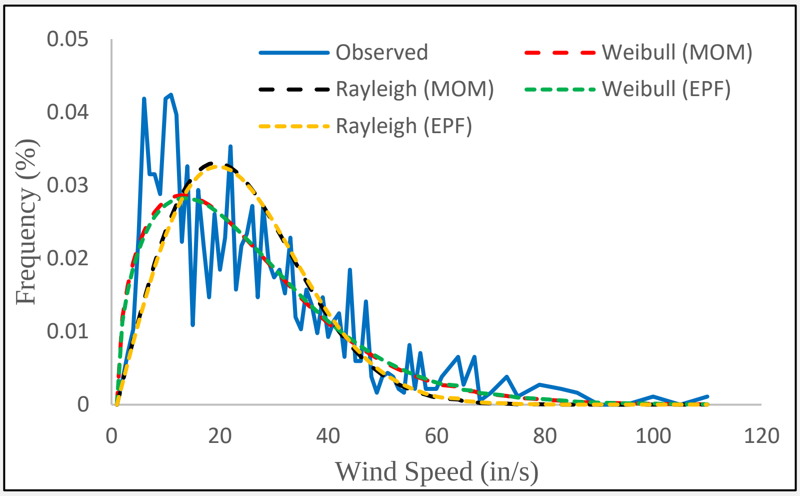

Figure 3. Wind speed distribution of Summer for Weibull PDF by MOM (Red dashed), EPF (Green dotted), Rayleigh by MOM (Black dashed), EPF (Orange dotted), and the observed data (Blue).

Figure 4 represents the observed wind data (Blue curve) compared to the PDFs of Weibull acquired by MOM (red dashed), EPF (green dotted), and Rayleigh obtained by MOM (black dashed), EPF (orange dotted) for the Summer (JJA) season. Here we can see that both the Weibull and Rayleigh obtained through MOM and EPF are very close, although the Weibull fits the observed data better. Moreover, compared to the previous two figures for Winter (Figure 2) and Spring (Figure 3), Figure 4 depicts a larger area of distribution confirming the higher wind speeds frequently occurring in the Summer season. In Figure 5, the observed data (blue) for Autumn (SON) is plotted against the Weibull by MOM (red dashed) and EPF (green dotted) as well as the Rayleigh by MOM (black dashed) and EPF (orange dotted). Here, the Weibull again seems to be better than the Rayleigh model with respect to the fitting of observed data. However, the area of the curve gets squashed, meaning the chance of observing high-speed winds gets smaller. In short, we can say that the Weibull model is a better fit to the observed data than Rayleigh, and the area of the distribution curve gets smaller as we move from cold to hot season. Furthermore, the Weibull curves are more right-skewed compared to Rayleigh curves. This feature may be due to the semi-arid nature of Tarnab's climate, as also shown by Saeed et al. (2021) for the same climate nature.

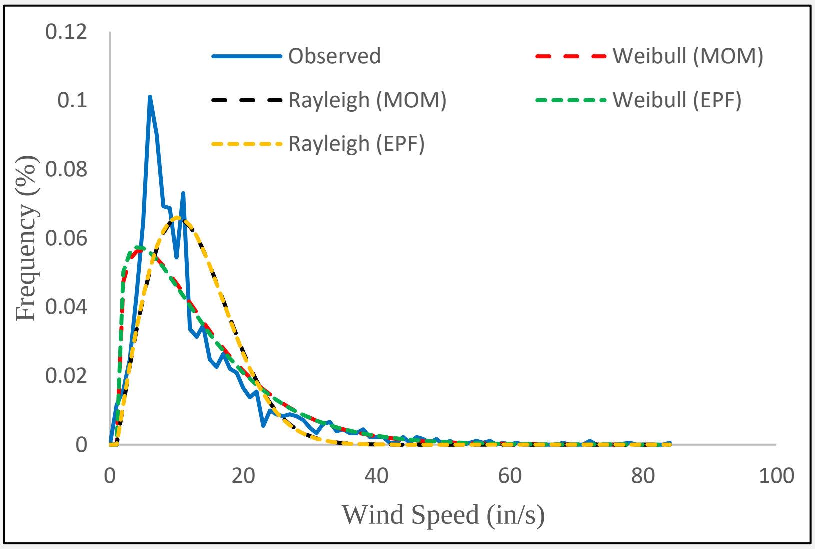

Figure 4. Wind speed distribution of Autumn for Weibull PDF by MOM (Red dashed), EPF (Green dotted), Rayleigh by MOM (Black dashed), EPF (Orange dotted), and the observed data (Blue).

Using equations 9-12, the useful wind speeds for all the seasons for both MOM and EPF are calculated and given in Table 5. The MP (u_{mp}) wind speeds for Weibull for the Winter and Autumn via both MOM and EPF are very low, meaning that Figures 2 and 5 are more rightly-skewed than Figures 3 and 4. The ME (u_{maxE}) carrying speeds lies in the tails of distribution curves as seen from Figures 2, 3, 4, and 5. Thereby, confirming usually low wind speeds for the region near the surface. The mean speeds predicted by Weibull ($\bar{u}_w$) are not only greater than those predicted by Rayleigh ($\bar{u}_R$) (see Table 5) but also match with the observed (see Table 4).

Table 5. Characteristic wind speeds in terms of Weibull and Rayleigh models for MOM and EPM

Method	Season	Weibull			Rayleigh		
		u_{mp}	$u_{max\,E}$	$\bar{u}_w$	u_{mp}	$u_{max\,E}$	$\bar{u}_R$
MOM	Winter	4.57	27.86	12.66	9.71	19.42	5.39
	Spring	10.52	39.29	20.05	15.69	31.38	8.71
	Summer	12.12	46.21	23.45	18.34	36.67	10.18
	Autumn	3.74	27.79	12.15	9.24	18.48	5.13
EPF	Winter	3.41	29.18	12.44	9.40	18.81	5.22
	Spring	8.98	41.41	20.02	15.54	31.07	8.62
	Summer	12.49	46.63	23.80	18.63	37.25	10.34
	Autumn	3.32	28.48	12.14	9.19	18.37	5.10

Equations 13-15 are employed for the construction of Table 6. It represents the MPE, MAPE, and RMSD values of Weibull and Rayleigh models under MOM and EPF. The MPE and MAPE values of the Weibull model via MOM are smaller (Khan et al., 2022) than those by EPF for the corresponding seasons; while with respect to RMSD, MOM is better than EPF only in the Winter and Spring seasons. Overall, MOM is better than EPF for the Weibull distribution. On the other hand, for the Rayleigh distribution, EPF proves to be better than MOM except for Summer with respect to MPE; MOM is superior to EPF except for Summer with respect to MAPE; and EPF is better than MOM for Winter and Autumn with respect to RMSD.

Table 6. Percent errors and RMSD values of seasonal Weibull and Rayleigh for MOM and EPF

Method	Season	Weibull			Rayleigh		
		MPE %	MAPE %	RMSD	MPE %	MAPE %	RMSD
MOM	Winter	6.47	36.37	0.0099	-27.90	52.82	0.0091
	Spring	11.82	43.44	0.0065	-17.21	40.79	0.0068
	Summer	12.05	49.03	0.0060	-8.44	47.20	0.0073
	Autumn	5.65	37.30	0.01	-29.49	48.13	0.0087
EPF	Winter	9.97	36.59	0.01	-30.18	52.85	0.0088
	Spring	16.79	47.07	0.0070	-18.34	41.56	0.0068
	Summer	13.32	49.54	0.0060	-6.58	47.12	0.0073
	Autumn	7.63	37.56	0.01	-29.89	48.24	0.0086

The findings presented in this work can be summarized as follows: the percent values of MOM are smaller than other parameter estimation methods, indicating that MOM is better than EPF, as supported by Khan et al. (2022) and Hussain et al. (2023); in comparison with Rayleigh distributions, Weibull is found to be more accurate (Azhar et al., 2019; Sumair et al., 2021); the shape factor (k) values obtained in this work [most of them in the annual data (Table 1) and all in the seasonal data (Table 4)] lie in the range of 1.2 to 2.75, which is deemed suitable for better results by the EPF method; the right-skewed Weibull curves for a semi-arid climate are also obtained by Saeed et al. (2021).

The study of wind speed distribution analysis shows that Tarnab has a diverse nature regarding wind speeds, ranging from very low to very high (several km/h), but low wind speeds dominate the distribution curves. The wind-driven forces, in addition to soaring temperatures, are the main sources of soil erosion and dryness, as well as lodging of many crops planted in Tarnab. Moreover, high-speed winds in dry weather lead to dehydration of the soil and negatively affect plants. Apart from its demerits, the wind speeds in the region can be used to produce power on a small scale for agricultural applications. Winds at heights greater than 10 m can be of use for this purpose.

CONCLUSION

In this study, two time series (annual and seasonal time scales) from 2004 to 2023 were examined for trends in wind speed using various approaches (Weibull and Rayleigh) and two methods of parameter estimation, i.e., MOM and EPF. The key findings of the study are:

1. Most of the kkk values in the annual data (Table 1) and all in the seasonal data (Table 4) lie in the range of 1.2 to 2.75, which has been proven to be an accurate range for the EPF method.
2. In both analyses (annual and seasonal), the Weibull distribution provides more accurate results than the Rayleigh distribution.
3. In the analysis of annual wind speeds, the MP speeds by Weibull were found to be greater than those of Rayleigh, whereas the ME carrying speeds by Weibull were smaller than those of Rayleigh (Table 1). The situation is reversed in the seasonal analysis of wind speed (Table 5). This is due to the dependency of MP and ME carrying wind speeds on the kkk and λ\lambdaλ parameters as well as the frequency of data points.
4. All curves of the Weibull distribution are right-skewed in the figures, indicating that the average values of the data are greater than the median.
5. In terms of statistical error analysis, MOM is proven to be better than EPF for both Weibull and Rayleigh distributions in the annual wind analysis. However, in the seasonal analysis, MOM is superior to EPF for the Weibull model. But in the case of Rayleigh, if one error analysis tool deems MOM to be more accurate, another deems EPF to be better.

Tarnab is an agricultural hub of the city of Peshawar. By utilizing wind resources along with other renewable technologies, the damage brought upon agriculture due to floods and drought in this region can be mitigated. Focusing more on wind analysis of the region may help in protecting crops from damage and offer implications for using wind as an energy source on a limited scale.

Although many studies cited in this work often reference the Weibull distribution in wind distribution analysis, it has limitations, such as being unsuitable for bimodal wind speed distribution data (Hussain et al., 2023). Moreover, it can be inferred that an hourly or other short-duration recording scheme of data would offer better results, which will be our goal for future studies of wind speeds. This study is only applicable to the ARI Tarnab region since we have only one meteorological station located at the site.

Additionally, other parametric and non-parametric methods can be employed to minimize the limitations of this study, along with the usage of modern electronic data loggers.

ACKNOWLEDGEMENTS

The authors extend their appreciation to the staff of Directorate of Soil and Plant Nutrition, Agriculture Research Institute Tarnab, Peshawar for their contribution in collecting the data which finally made this work possible. Further, the authors admit that no fundings were taken for conduction of this research.

AUTHOR DECLARATION

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Aamir Khan: Data curation, Software, Formal analysis, Investigation, Validation, Writing-original draft, Project administration, Methodology. **Amna Shafi:** Conceptualization, Software, Supervision, Methodology, Writing- review and editing, Formal analysis, Investigation, Software.

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