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Assessment of wind energy potential along the Egyptian Mediterranean Coast

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Abstract

Background Currently, there is no wind park operating along the Egyptian Mediterranean Coast. Therefore, this study aims to find suitable locations for such projects. Wind data from five coastal meteorological stations were used. These are Marsa Matruh (MM), Ras El-Tin (RE), Abu Qir (AQ), Port Said (PS), and Arish (Ar), in that order from west to east. The wind regime dataset, comprising velocity and direction measurements at a 10-m elevation, was collected from January 2007 to December 2022 (16 years), with a complete record of all data points. The Weibull distribution function, along with its different parameters, was used to characterize wind energy along the Egyptian Mediterranean Coast. The coefficient of determination (R^2), root mean squared error (RMSE), and relative root mean squared error (RRMSE) for the Weibull parameters, along with the relative percentage errors (RPE) for the wind power density were calculated to assess the concordance between outcomes derived from observed data and those predicted by the Weibull function.

Results Results revealed that the dominant wind direction along the Egyptian Mediterranean Coast was the NNW to N wind, except at Ar where the dominant wind was S. The wind velocity range of 4–6 m/s dominated RE, AQ, and PS. At MM and Ar, this was reduced to 2–4 m/s. The analysis of wind power density outlined significant insights into the potential for wind energy generation in the region. The overall analysis showed that AQ and PS were potentially the most suitable locations for wind energy projects. However, the high variability at the AQ site required robust system designs to manage the fluctuating wind conditions. PS might be more suitable for projects prioritizing stability and consistency over maximum energy output. Although Arish, characterized by its lower wind power density, may be less conducive for large-scale wind energy projects, it could still be viable for smaller installations or when integrated with other renewable energy sources.

Conclusions The different statistical indices reflected good model fitting, displaying the reliability of the Weibull distribution as a tool for preliminary wind resource assessment along the Egyptian Mediterranean Coast and facilitating accurate predictions of wind power availability.

Keywords Egypt, Mediterranean Sea, Wind energy, Renewable energy, Weibull function

Background

Nowadays, the world's energy needs are growing to achieve the ambitious development objectives underway. The rate of energy consumption has been expected to increase by an average of 2.0% each year between 2003 and 2030 [1]. Since the industrial revolution in the late 1800s, the development processes have depended mainly on traditional fossil fuel energy resources such as coal and oil. However, these traditional resources have

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been recognized to contribute to almost one-third of the greenhouse gas (GHG) emissions all over the world [2], resulting in the catastrophic climate change issue. Additionally, the accelerated demand eventually hastens the depletion of fossil fuel reserves. In this track, the United Nations established the Sustainable Development Goals (SDGs) to ensure a more sustainable future for everybody.

Among the diverse renewable energy resources explored worldwide, wind energy is of particular interest. Recently, wind energy has become more popular as a renewable energy source, and scholars are trying to develop the wind energy sector in order to achieve high reliability in renewable energy systems [3]. The primary reason for this is that the resource is highly competitive due to its clean, abundant, easily harvested, limitless, and cost-effective nature [2, 4, 5]. The development in the wind energy sector has been driven by various factors, including industrial maturation (e.g., turbine size), economic benefits (e.g., auctions offered), and financial matters (e.g., steel price and debt interest rates) [6].

Wind resources can be explored using either onshore or offshore wind regimes. While the former is the power generated by wind turbines installed on land driven by the regular movement of the air, the latter is the power used to generate electricity from wind blowing across the open sea. Due to the higher wind speeds, greater consistency, and lack of physical interference from the land or man-made objects, offshore wind farms are thought to be more efficient than onshore ones [7]. Offshore wind exploitation is still more expensive than onshore, despite the fact that offshore wind costs have dropped dramatically in recent years, diminishing the gap between the two. Fortunately, experts predict that, by 2050, onshore and offshore wind energy costs will drop by 37–49%, making them 50% less expensive than anticipated in 2015 [6].

The worldwide installed wind power capacity from the two resources reached 564 GW in 2018 [5]. In 2021, 93% of the total 830 GW of installed wind capacity was onshore, with the remaining 7% being offshore wind farms. Onshore wind is a mature technology that is available in 115 nations worldwide, whereas offshore wind is still in its early stages of development, with capacity present in only 19 countries [8]. The contribution of the two resources increased to 906 GW in 2022 [9].

Energy consumption in the Mediterranean region will increase by more than 50% until 2040 [10]. South and East Mediterranean countries would grow quickly as a result of population trends and economic expansion, whereas North Mediterranean countries would see a steady decline in energy demand [11]. Electricity demand in the South and East Mediterranean is predicted to nearly triple by 2040, with 60% generated from renewable energy resources, mainly solar and wind [10]. Regarding the wind field, the Mediterranean is characterized by a high wind potential [10] with a dominant role of northwesterly winds over the entire basin moderated by the existence of intricate coastlines and islands [12].

Due to its significant location among various reasons, Egypt plays an important role in the global energy industry [13]. Egypt has set an ambitious goal of generating 42% of its energy capacity from renewable sources by 2035, termed the 2035 energy target [14]. Since the government's New & Renewable Energy Authority (NREA) launched a pilot wind energy plant in Hurghada in 1988, the country has become one of the pioneering countries for wind energy in Africa and the Middle East. The Wind Atlas of Egypt, which was released in 2006, stated that the nation possessed abundant wind energy potential, particularly along the Gulf of Suez. This is considered one of the best locations in the world for collecting wind energy due to its high consistent wind speeds that average between 8 and 10 m/s at a height of 100 m, as well as the availability of wide deserted desert expanses. Additionally, the Atlas clarified that the Egyptian Mediterranean Coast had an excellent wind regime, reaching 7 m/sec. Thanks to the lofty goals announced on the fringes of the COP27, which will take place in Sharm El-Sheikh, Egypt, in November 2022, Egypt is now prepared to reclaim its position as a major player in the worldwide wind energy industry. In fact, only a few studies have been performed to assess wind power and its applications in Egypt. This includes the studies of [1, 15–20]. With so few publications, one can easily assume that not much is known about the current condition of wind energy potential along the shores of Egypt.

There are various distribution functions for determining a site's wind energy potential [5, 21, 22]. Because of its precision, flexibility, and computational simplicity, the Weibull probability distribution is commonly employed in academic literature to evaluate wind power capacity [5, 23–28]. The Weibull probability distribution is featured by two main parameters: the shape parameter (k) and the scale parameter (c) which are essential to determine the wind field characteristics.

At present, no wind parks are operational along the Egyptian Mediterranean Coast. Thus, the main objective of this study is to identify suitable locations for such projects. This is achieved by the following: (1) analyzing the wind patterns at divergent points along the Egyptian Mediterranean Coast over 16 years (2007–2022); (2) assessing the wind energy potential using the Weibull probability distribution function; and (3) selecting the most appropriate site among those studied for wind energy generation.

Methods

The Egyptian Mediterranean Coast (Fig. 1), which stretches approximately 1170 km from Sallum (west) to Rafah (east), borders the southern Levantine Basin. In this study, wind data were obtained from five coastal meteorological stations (Fig. 1 and Table 1). Each station measured the hourly wind regime (speed and direction) at a 10 m height above the ground. The study spans 16 years, from January 2007 to December 2022. Throughout the study, these stations had no missing data.

We employed Windographer® software (version 5.2.9) to evaluate the variability and intensity of wind speeds at the five stations. This software facilitated the application of four distinct algorithms—maximum likelihood,

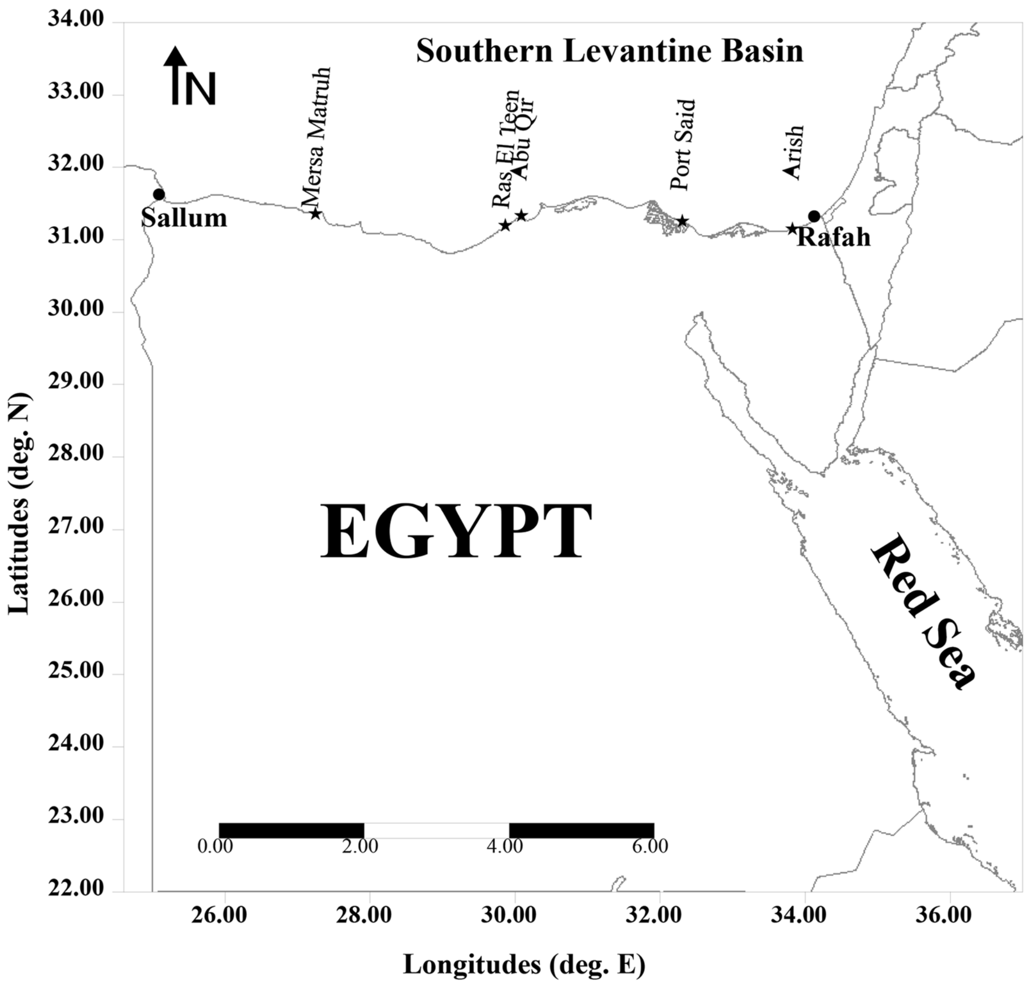

Fig. 1 Boundaries of the Egyptian Mediterranean Coast (·) and the five meteorological coastal stations (*) used in this study

Table 1 Information on the coastal meteorological stations used in this study

	Station name	Station no.	Latitude (N)	Longitude (E)	Height above MSL (m)	Distance to the shoreline (m)
1	Marsa Matruh (MM)	62,304	31° 21′ 34″	27° 14′ 43″	20	425
2	Ras El-Teen (RE)	62,317	31° 11′ 50″	29° 51′ 49″	21.95	365
3	Abu Qir (AQ)	62,320	31° 19′ 55″	30° 05′ 06″	26.6	15
4	Port Said (PS)	62,334	31° 15′ 19″	32° 18′ 17″	19.75	52
5	Arish (EA)	62,331	31° 08′ 54″	33° 49′ 27″	15	490

least squares, WAsP, and Openwind—to model the wind speed distributions, enabling a detailed comparison of their efficacy in capturing the wind energy potential inherent to each location.

Weibull parameters and model fit:

The analysis was based on determining the Weibull shape (k) and scale (c) parameters for each algorithm, as well as calculating the coefficient of determination (R^2), which offers a quantitative evaluation of how well each model aligns with the observed wind speed data. These parameters are instrumental in understanding the wind speed's variability and average intensity, which directly influence a location's wind power generation abilities. The results highlight that higher (k) values, indicating increased variability in wind speed distribution, and higher (c) values, denoting higher average wind speeds, are beneficial for optimizing wind energy capture. The R^2 values served as a critical indicator of model accuracy, with values closer to 1 denoting a better representation of the wind speed distributions.

Selection of the optimal algorithm:

According to the comprehensive evaluation, the least squares algorithm was identified as the most suitable for modeling wind speed distributions and assessing wind energy potential along the Egyptian Mediterranean Coast. This decision was informed by the following:

1. High R^2 values: Demonstrating an excellent fit between modeled and observed wind speeds across the stations is crucial for accurate wind energy assessments.
2. Balanced parameter estimation: Offering a well-rounded representation of wind speed variability and intensity is essential for evaluating wind power potential.
3. Versatility across locations: Showcasing robust performance and adaptability takes place in diverse geographical conditions along the Mediterranean coast.

The intricate comparison of Weibull parameters and R^2 values across different modeling algorithms illuminates the complexities of wind speed distributions and underscores the significance of selecting an appropriate modeling approach for wind energy analysis. The least squares algorithm, with its exemplary performance and adaptability, stands out as a versatile and reliable tool for wind energy assessments, facilitating informed decision-making in the development of wind power projects along the Egyptian Mediterranean Coast.

Probability distribution functions are often used to assess the power characteristics in the recorded wind speed data. The two-parameter Weibull probability distribution function (Eq. 1) is widely used to characterize the distribution of wind speeds measured regularly throughout a month, year, or several years [25]. The density of wind energy and wind speed parameters can be efficiently evaluated using this approach. Furthermore, in most commercially accessible systems, this two-parameter Weibull distribution function is employed to estimate annual energy output [2]:

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

where $f(V)$ is the Weibull probability function of the wind speed V (m/s), k is the shape parameter, and c is the scale parameter of the probability function.

Equation (2) gives the cumulative distribution function of the observed wind speed V (m/s):

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

The average and standard deviation of the wind speed series can be mathematically expressed by Eqs. (3) and (4), respectively [25]:

$$V_m = c\Gamma\left[\frac{1}{k} + 1\right], \tag{3}$$

$$\sigma = c\left[\Gamma\left(\frac{2}{k} + 1\right) - \Gamma^2\left(\frac{1}{k} + 1\right)\right]^{1/2}, \tag{4}$$

where V_m is the average wind speed (m/s), σ is the standard deviation of the recorded wind speed data, and Γ is the gamma function as per Euler's second-kind integral.

The Weibull distribution Eq. (1) is valid for $k > 1$ and $c > 0$. The shape factor (dimensionless) normally falls between 1 and 3 [2]. When considering a specific average wind speed, a lower form factor denotes a wider distribution of wind speeds about the average, whereas a larger shape factor signals a relatively tight distribution of wind speeds around the average [5]. Normal energy production for a given average wind speed will increase with a lower shape factor [5].

The Weibull shape parameter (k), for $1 \leq k < 10$, is given by Eq. (5) [25, 26, 29]:

$$k = \left(\frac{\sigma}{V_m}\right)^{-1.086}. \tag{5}$$

The Weibull scale parameter (c) is given by Eq. (6) [2, 25]:

$$c = \frac{V_m}{\Gamma\left(\frac{1}{k}+1\right)}. \tag{6}$$

The shape (k) and scale (c) parameters can be used to estimate the wind power (W/m^2) on both monthly and annual basis [17]:

$$P = 0.5\rho c^3 \Gamma\left(\frac{3}{k}+1\right) \tag{7}$$

The theoretical available wind power (Watt) can be calculated as [16]:

$$\begin{aligned} &P = 0.5\rho A V^3 = 0.635 A V^3; \\ &\text{for air density } \rho = 1.225\,\text{kg/m}^3, \end{aligned} \tag{8}$$

where A (m^2) is the area in which the blade of a wind turbine rotates.

The extracted wind power depends on the efficiency of the energy conversion system, which is estimated to be at least 40% of the available kinetic energy in the wind regime [16, 17]. Therefore, for a swept unit area, the maximum extractable wind power is given as:

$$P = 0.254\,\mathrm{V}^3\,\mathrm{W/m}^2. \tag{9}$$

Results

Statistical analysis of wind regime along the Egyptian Mediterranean Coast

Table 2 presents a comprehensive overview of wind characteristics at the five meteorological stations along the Egyptian Mediterranean Coast. These statistics are pivotal in assessing the wind energy potential in the region. Throughout the study period, the average wind speeds ranged from 3.91 m/s at Arish (Ar) to 5.73 m/s at Abu Qir (AQ), with the latter station showing the highest potential for wind energy generation based on this criterion. These values provide a baseline for estimating the amount of energy that could be harvested, considering that wind power is proportional to the cube of wind speed.

The maximum recorded wind speeds (ranging up to 25.72 m/s at Ar) highlight the potential for high energy yield periods. However, such high speeds also necessitate robust turbine designs to withstand extreme conditions. The minimum wind speeds, 0.00 m/s at all stations, indicate calm periods when wind turbines may not produce energy.

As for the wind direction, MM, RE, AQ, and PS stations shared a similar dominant direction (NNW) around 320° to 330°, indicative of north-westerly winds prevalent in these areas. In contrast, Ar experienced a different pattern with a dominant southerly (S) wind (180°), suggesting regional variations in wind flow patterns along the coast.

Furthermore, the frequency distribution of wind speeds, categorized into intervals of 2 m/s, is presented for each meteorological station (Table 3). At MM, the wind speeds predominantly ranged from 2 to 4 m/s, accounting for approximately 28.3% of the time. This frequency distribution suggests a substantial presence of moderate wind speeds, which are generally favorable for wind energy generation. Both RE and AQ showed significant wind speeds in the 4–6 m/s interval (27.3%), indicating a reliable wind resource for energy production. This distribution denotes a robust wind energy potential, with a substantial portion of wind speeds falling in the more energetic categories that are beneficial for higher energy yields. PS demonstrated consistency in wind speeds, particularly in the 4–6 m/s and 2–4 m/s ranges, which, respectively, constitute 33.6% and 31.1% of the wind speed occurrences. Contrastingly, Ar exhibited a distinct pattern with a higher frequency of lower wind speeds (2–4 m/s range, 35.8%). However, there remains a considerable amount of time (26.6%) with wind speeds within the 4–6 m/s range, signifying a potential for wind energy exploitation, albeit at a lower scale compared to other stations.

Table 2 Statistics of the wind regime along the Egyptian Mediterranean Coast (2007–2022)

Station	Dominant direction (°)	Mean wind speed (m/s)	Std. deviation (m/s)	Min wind speed (m/s)	Max wind speed (m/s)
MM	320	4.73	2.85	0.00	24.18
RE	330	5.32	2.74	0.00	23.66
AQ	330	5.73	2.67	0.00	23.15
PS	330	4.66	2.10	0.00	20.58
Ar	180	3.91	2.25	0.00	25.72

Table 3 Wind speed frequencies along the Egyptian Mediterranean Coast (2007–2022)

Wind speed range (m/s)	MM (%)	RE (%)	AQ (%)	PS (%)	Ar (%)
0–2	17.8	10.8	8.1	9.8	20.2
2–4	28.3	25.6	22.6	31.1	35.8
4–6	24.1	27.3	27.3	33.6	26.5
6–8	15.6	19.7	21.7	18.7	12.4
8–10	8.3	10.5	12.5	5.7	4.0

Wind speed in relation to wind energy production

Wind turbines typically begin generating electricity at a certain minimum speed, known as the "cut-in" speed, usually around 3–4 m/s [30–32]. Wind speeds above 25 m/s frequently cause turbines to shut down for safety; this is known as the "cut-out" speed. Turbines operate best at greater speeds. The defined ranges for this analysis (Table 4) are as follows: below cut-in (0–3 m/s), representing low wind speeds insufficient for standard wind turbines; cut-in to moderate (3–6 m/s), indicating the minimum operational range for turbines; moderate to optimal (6–12 m/s), which is the ideal operational range for most turbines; above optimal to cut-out (12–25 m/s), denoting high wind speeds near safety limits; and above cut-out (> 25 m/s), where turbines are shut down for safety. Results unveiled that, throughout the period of investigation, MM exhibited a balanced distribution with 27.38% of the time below cut-in and a significant 31.13% in the moderate-to-optimal range, signifying a good potential for wind energy generation. RE had a lower occurrence of low wind speeds (17.15% below cut-in) and a higher prevalence in the moderate-to-optimal range (36.09%), highlighting its consistency for wind energy production. AQ stood out with the lowest percentage of time in the below cut-in range (11.88%) and the highest in the moderate-to-optimal range (41.18%), suggesting excellent potential for efficient wind power generation. PS exhibited a higher frequency in the cut-in to moderate range (58.39%) but a lesser extent in the moderate-to-optimal range (25.29%), pointing to more consistent but generally lower wind speeds. Ar had the highest percentage of time in the below cut-in range (34.99%), indicating less consistency for standard turbine operation, though the presence of 18.68% in the moderate-to-optimal range offers some potential.

Weibull distribution

Wind speed distribution analysis using Weibull functions along the Egyptian Mediterranean Coast

The Weibull probability density function (PDF) plots (Fig. 2), derived for each of the five meteorological stations along the Egyptian Mediterranean Coast, provide a detailed representation of the wind speed distributions at these locations. These plots, characterized by distinct colors and enhanced readability through larger fonts, offer critical insights into the nature and variability of wind speeds, which are fundamental for evaluating wind energy potential.

AQ and PS exhibited the highest (k) values (2.308 and 2.424, respectively), suggesting significant variability in wind speeds, which is advantageous for capturing higher wind energy potential. The Weibull scale parameter (c) further accentuates these insights (Table 5). AQ displayed the highest scale parameter ($c = 6.505$), correlating with higher wind speeds, while Ar had the lowest scale parameter ($c = 4.496$), aligning with a lower range of wind speeds. These parameters are instrumental in quantifying the wind speed characteristics at each station, with higher scale values indicating greater wind energy potential.

Stations with higher shape parameters, such as AQ and PS, exhibited less variability in wind speeds, suggesting a more stable and predictable wind regime. This stability is crucial for the consistent operation of wind turbines and efficient energy production. Conversely, stations like RE and Ar showed lower shape parameters, indicating greater variability and thus a potentially less reliable wind energy source. The scale parameter further enhances this concept. With the largest size parameter, the AQ station stood out and might be subject to greater average wind speeds, which were favorable for the capture of wind energy. The moderate scale parameter presented MM as a viable option, though it might not reach the efficiency levels of AQ or PS. The lower scale parameters at RE and Ar stations point towards a reduced average wind speed, potentially limiting their effectiveness as wind energy sites.

Table 6 displays some goodness-of-fit parameters such as the coefficient of determination (R^2), root mean square error (RMSE), and relative root mean square error (RRMSE) for the Weibull parameters for the wind speed data across the considered five meteorological stations. These are handy tools to statistically compare

Table 4 Wind speed consistency for turbine operation along the Egyptian Mediterranean Coast (2007–2022)

Station	Below cut-in (0–3 m/s) (%)	Cut-in to moderate (3–6 m/s) (%)	Moderate to optimal (6–12 m/s) (%)	Above optimal to cut-out (12–25 m/s) (%)	Above cut-out (> 25 m/s) (%)
MM	27.38	40.19	31.13	1.30	0.00
RE	17.15	44.53	36.09	2.23	0.00
AQ	11.88	44.64	41.18	2.30	0.00
PS	16.05	58.39	25.29	0.27	0.00
Ar	34.99	46.09	18.68	0.24	0.07

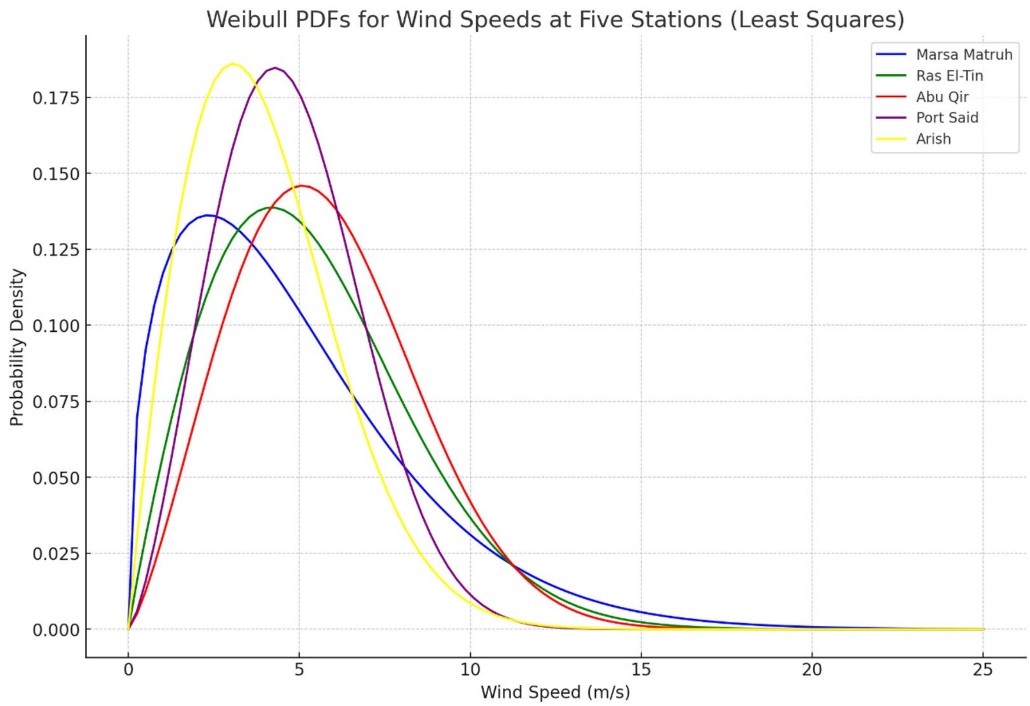

Fig. 2 Weibull PDFs at the five stations of interest along the Egyptian Mediterranean Coast

Table 5 Shape parameter (*k*) and scale parameter (*c*) at the five stations of interest along the Egyptian Mediterranean Coast

Station	Shape parameter (*k*)	Scale parameter (*c*)
MM	1.431	5.417
RE	1.943	6.069
AQ	2.308	6.505
PS	2.424	5.335
Ar	1.923	4.496

Table 6 Summary of Weibull distribution fit metrics for wind speed data across the five meteorological stations

Station	R^2	RMSE	RRMSE
MM	0.7312	0.002002	0.002476
RE	0.7877	0.001067	0.001351
AQ	0.8514	0.000764	0.000986
PS	0.8466	0.000778	0.000954
Ar	0.7514	0.001486	0.001732

between the powers obtained with the measured data and the Weibull.

The R^2 values ranged from 0.7312 (MM) to 0.8514 (AQ), reflecting a good level of model fit. The variability in R^2 values across stations may be influenced by local environmental factors, such as terrain complexity and coastal effects, which can affect wind speed distribution characteristics. The RMSE and RRMSE metrics remain low across all stations, suggesting that the Weibull distribution model's predictions are close to the observed values. The lowest RMSE and RRMSE are noted for Abu Qir, aligning with its higher R^2 value, whereas Arish shows the highest RMSE and RRMSE, indicating greater deviation between the predicted and observed wind speeds.

Analysis of wind speed probabilities across the Egyptian Mediterranean Coast stations using Weibull cumulative distribution functions

The Weibull cumulative distribution function (CDF) plots, characterized by distinct color schemes for each station, reveal significant insights into the probability distributions of wind speeds. These visualizations, complemented by the detailed data in the accompanying table, provide a robust framework for assessing the wind energy potential at these sites.

The CDF curves for the five considered stations (Fig. 3) encapsulate the cumulative probabilities of encountering specific wind speeds. For instance, stations like AQ and PS, with steeper CDF curves, demonstrate a higher probability of experiencing moderate-to-high wind speeds, indicative of favorable conditions for wind energy harnessing. In contrast, the relatively flatter curves for RE

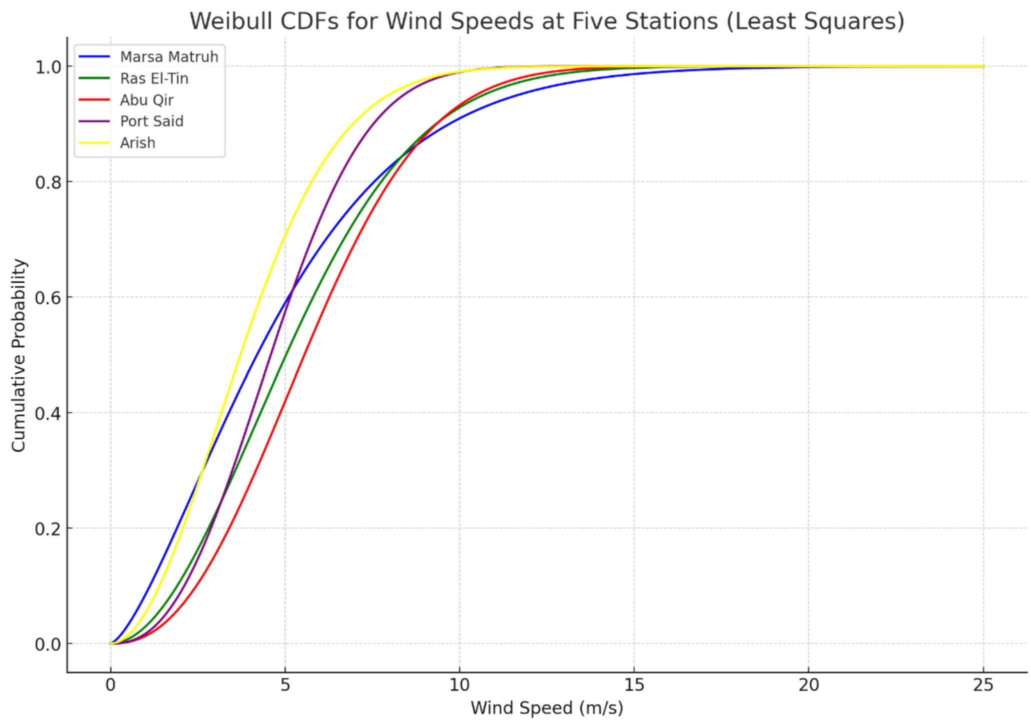

Fig. 3 Weibull cumulative density function curves for the five stations of interest along the Egyptian Mediterranean Coast

and Ar suggested a wider spread of wind speeds with a significant proportion of lower speeds.

The CDF plot for MM demonstrates a relatively gradual ascent, suggesting a more even distribution of wind speeds, including higher speeds. This elucidates that wind speeds conducive to energy generation are reasonably probable, making it a favorable site for wind energy projects. The CDF plot for RE shows a steep initial rise, denoting a high probability of lower wind speeds. However, the curve also extends to higher wind speeds, suggesting occasional occurrences of strong winds. This variability is crucial for planning energy capture and storage systems. The AQ CDF plot exhibits a steeper slope in the lower wind speed range and a more gradual incline at higher speeds. This implies that although the station encounters a considerable amount of moderate-to-high wind speeds, lower wind speeds are equally frequent, underscoring its potential for reliable wind energy production. The CDF curve for PS rises more steadily, implying a broader distribution of wind speeds and a higher likelihood of moderate wind speeds. This station may offer a balance between the frequency and intensity of wind speeds suitable for energy production. Lower wind speeds appear to be more common, according to the Ar CDF plot, which shows a sharp rise and early plateau at the lower end of the curve. This pinpoints that the wind speed potential is restricted, which may make it less appropriate for large-scale wind energy projects. Nonetheless, it might be worth considering for smaller-scale installations or in combination with other renewable energy sources. The cumulative probabilities of wind speed ranging from 1 to 10 m/s at each station along the Egyptian Mediterranean Coast are illustrated in Table 7.

Wind power along the Egyptian Mediterranean Coast

The analysis of wind power density across the five meteorological stations along the Egyptian Mediterranean Coast (Table 8) discloses significant insights into the potential for wind energy generation in the region. AQ exhibited the highest mean wind power density of 169.42 W/m^2, suggesting a notably higher potential for wind energy exploitation compared to other locations. This

Table 7 Cumulative probabilities of wind speeds at the Egyptian Mediterranean stations

Wind speed	MM	RE	AQ	PS	Ar
CDF at 5 m/s	0.590	0.497	0.420	0.575	0.707
CDF at 10 m/s	0.910	0.929	0.933	0.990	0.990
CDF at 15 m/s	0.986	0.997	0.999	0.999995	0.999961
CDF at 20 m/s	0.998	0.999961	0.999998	1.00000	1.00000
CDF at 25 m/s	0.999867	1.00000	1.00000	1.00000	1.00000

Table 8 The calculated wind power criteria along the Egyptian Mediterranean Coast (2007–2022)

St.	Mean (W/m^2)	Standard deviation (W/m^2)	Min. (W/m^2)	25th percentile (W/m^2)	Median (W/m^2)	75th percentile (W/m^2)	Max. (W/m^2)
MM	109.05	166.14	0.00	19.95	54.28	132.42	2464.33
RE	149.45	243.04	0.00	32.33	76.31	162.87	4743.43
AQ	169.42	236.73	0.01	47.54	97.69	193.99	2764.72
PS	79.78	84.42	0.24	32.89	56.67	96.54	1082.24
Ar	50.74	66.92	0.00	17.64	32.33	56.67	1382.74

is further underscored by its maximum recorded wind power density of 2764.72 W/m^2, indicating substantial peak wind energy generation capabilities. In contrast, Ar demonstrated a relatively lower mean wind power density of 50.74 W/m^2, with a maximum of 1382.74 W/m^2, reflecting more modest wind energy prospects.

The variability in wind power density, as indicated by the standard deviation, was pronounced at the RE station, with a value of 243.04 W/m^2. This implied a high degree of fluctuation in wind power at this station, which could impact the consistency of wind energy generation. PS, however, showed a lower variability with a standard deviation of 84.42 W/m^2, alongside a mean wind power density of 79.78 W/m^2, pointing to more stable but moderate wind energy potential.

The distribution of wind power densities, represented by the 25th, 50th (median), and 75th percentiles, further illuminates the typical range of wind energy conditions at each station. For instance, the median wind power density at MM is 54.28 W/m^2, with a 75th percentile of 132.42 W/m^2, stipulating that wind power density frequently reaches considerably high levels, conducive to effective wind energy harvesting.

The box plot visualization (Fig. 4), depicting the wind power density across the five meteorological stations along the Egyptian Mediterranean Coast, offers valuable insights into the variability and potential of wind energy at each location. Planning and assessing the viability of wind energy projects in the area depend heavily on the distinctive features that each station displays in terms of wind power density. At MM, the box plot expresses a moderate range of wind power densities with a fairly high median, indicating consistent wind energy potential with occasional peaks. The outliers in the data suggest sporadic periods of very high wind power, which could be leveraged for enhanced energy generation. The RE station shows a wider interquartile range and notable outliers, displaying significant variability in wind power. Although less predictable, this station's highest value emphasizes periods of exceptionally high wind power density, which

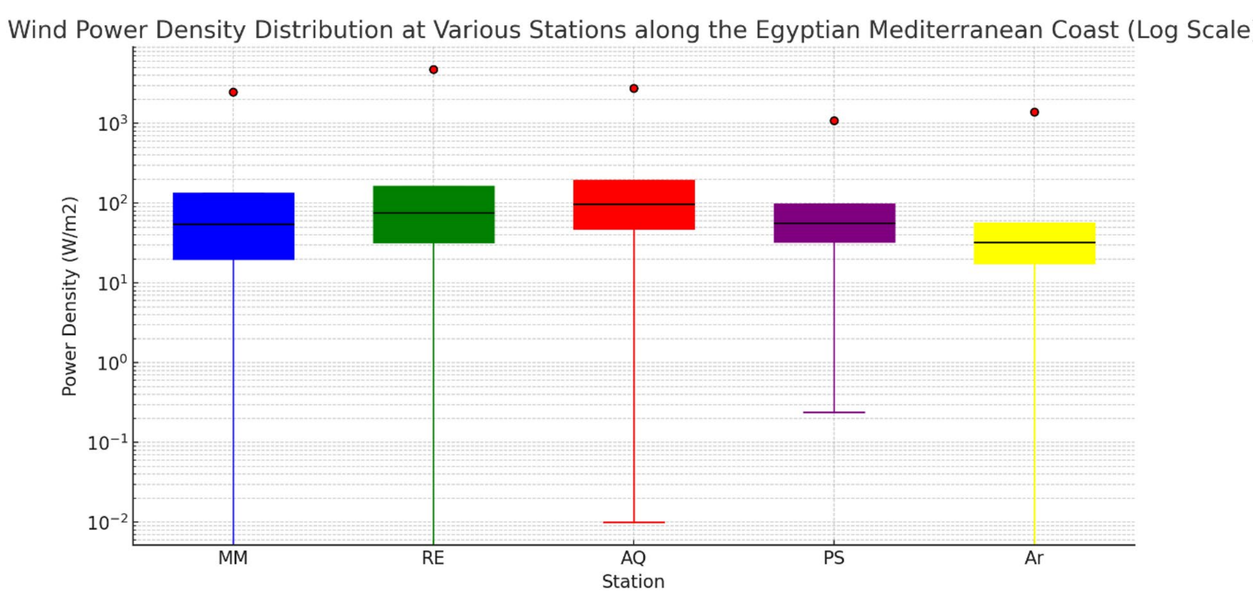

Fig. 4 The wind power box plot at the five stations of interest along the Egyptian Mediterranean Coast

reflects a potential for high-yield wind energy generation. AQ stood out with the highest median wind power density, pointing to its strong potential as a wind energy site. However, the wide interquartile range and outliers elucidate that wind power density at this station can vary substantially, which is an important consideration for energy reliability and storage solutions. PS exhibits a narrower interquartile range with fewer and less extreme outliers. This stipulates more stable wind conditions, making it a potentially reliable site for consistent wind energy production, albeit at a generally lower intensity compared to other stations. Lastly, the Arish station displays a lower median and a narrower range in wind power density, suggesting that it has the most modest wind energy potential among the stations. The fewer and less pronounced outliers in its box plot further underscore the station's limited variability in wind power.

Table 9 presents a detailed summary of the Weibull distribution parameters: shape parameter (k) and scale parameter (c), alongside the Weibull-estimated wind power densities and the relative percentage errors (RPE) for the considered meteorological stations. This comprehensive analysis provides valuable insights into the suitability of the Weibull distribution for estimating wind power densities, a critical factor in wind energy research and development. The following discussion elaborates on these findings and their implications for the field of renewable energy. As mentioned before, the shape (k) and scale (c) parameters of the Weibull distribution vary across stations, reflecting the diversity in wind speed distributions influenced by local geographical and meteorological conditions. For instance, the higher (k) value at AQ suggests a narrower distribution of wind speeds around the mean, marking more consistent wind conditions compared to other stations. The Weibull-estimated wind power densities range significantly across the stations, from as high as 213.23 W/m^2 at MM to as low as 77.26 W/m^2 at Ar. This variation underscores the impact of local wind speed characteristics on the potential for wind energy generation, highlighting the importance of site-specific assessments in wind farm development. The RPE values are remarkably low across all stations, with the highest being only 0.075% at Ar and the lowest being 0.009% at both RE and AQ. Such minimal discrepancies between the Weibull-estimated wind power densities and directly provided or calculated values underscore the high precision of the Weibull distribution in modeling wind energy potential.

The consistently low RPE across diverse environmental settings reinforce the reliability of the Weibull distribution as a tool for preliminary wind resource assessment along the Egyptian Mediterranean Coast, facilitating accurate predictions of wind power availability.

Table 9 Comparison of Weibull-estimated and directly provided wind power densities across the five meteorological stations

Station	Weibull k	Weibull c	Weibull power density (W/m^2)	RPE (%)
MM	1.431	5.417	213.23	0.061
RE	1.943	6.069	187.82	0.009
AQ	2.308	6.505	196.68	0.009
PS	2.424	5.335	104.64	0.035
Ar	1.923	4.496	77.26	0.075

Discussion

The evaluation of a wind-energy resource is primarily based on assessing the statistics of the wind regime: speed and direction. The mean wind speed provides a baseline for estimating the amount of energy that could be harvested at any location, considering that wind power is proportional to the cube of wind speed. This average was previously calculated over different periods at different locations at 10 m height along the Egyptian Mediterranean Coast (Table 10).

As shown, the present mean wind speed at the five examined locations is in good agreement with the results of the previous studies. As for the wind direction, statistics of the present research declared a dominant NNW to N winds along the Egyptian Mediterranean Coast in MM, RE, AQ, and PS. This has been previously concluded for the four locations [20, 33–35]. The dominant southern wind at Ar has been previously determined [33]. Although the current results explained that the wind speed range of 2–4 m/s dominated MM, [7] declared a dominant wind class (3–6 m/s) in MM at 80 m height based on satellite data. The primary wind speed ranges determined in this work for PS concurred with those determined earlier [34]. This consistency was advantageous for steady and predictable wind power generation.

Table 10 Previously calculated mean wind speed (m/s) along the Egyptian Mediterranean Coast

MM	Alexandria	PS	AR
4.5 [18]	4.8 [15]	4.6 [20]	2.35 [17]
5.6 [15]	4.4 [17]	3.9 [35]	2.4 [20]
5.0 [17]	4.0 [20]	5.3 [34]	4.0 [33]
5.3 [20]	4.17 [39]	4.7 [33]	3.91 (the present study)
4.6 [33]	5.5 (the present study)	4.66 (the present study)	
4.73 (the present study)			

The cut-out speed at MM throughout the present study period was in the range of 12–25 m/s. This was previously declared to be 15 m/s over 29 years of analysis [15]. The cut-in speed in Alexandria calculated over 29 years was 3.0 m/s and the cut-out speed was 12.0 m/s [15]. The shape and spread of the Weibull probability density functions (PDFs) vary notably among the five investigated stations along the Egyptian Mediterranean Coast. For instance, AQ and PS exhibited narrower and more pronounced peaks in their PDFs, indicative of a higher concentration of wind speeds around a specific value. This suggests a more consistent wind regime, which is favorable for wind energy applications, as it implies predictability and reliability in wind speed patterns.

The shape (k) and scale (c) parameters were previously calculated at MM, Alexandria, PS, and Ar (Table 11).

As shown, the present results are somehow far from the previous results for the different locations. Either the applicable equations used to determine the parameters or the differences in the time of concern could be the cause of these variances. This comparative analysis of Weibull parameters is a cornerstone in identifying the most promising locations for wind energy projects. AQ and PS, with their higher values in both parameters, are identified as the most suitable sites for wind farm development. MM, while not at the forefront, still holds potential. In contrast, RE and Ar require cautious consideration, potentially necessitating advanced technological adaptations or serving as secondary or complementary energy sources. The Weibull cumulative distribution function (CDF) offers a comprehensive view of the wind speed variability across different meteorological stations along the Egyptian Mediterranean Coast. The CDF elucidates that, at certain stations, such as AQ and PS, the likelihood of wind speeds exceeding moderate values (e.g., 5 m/s) is considerably high, affirming their suitability for wind energy projects. Conversely, stations like RE and Ar exhibit higher probabilities for lower wind speeds, thus necessitating a more nuanced approach to wind energy exploitation. The combination of the Weibull CDF plots and the detailed probability table forms an integral part of the wind resource assessment, allowing for a nuanced understanding of wind speed distributions and their implications for wind energy potential along the Egyptian Mediterranean Coast. The calculated mean wind power density in this study (Table 8), at the different locations along the Mediterranean Coast, is in agreement with those previously calculated at MM (195 W/m^2, [17]) (94.32 W/m^2, [20]); Alexandria (134 W/m^2, [17]) (41.20 W/m^2, [20]); PS (61.89 W/m^2, [20]) (83.0 W/m^2, [35]); and Ar (30.69 W/m^2, [17]) (8.71 W/m^2, [20]). Within the Eastern Mediterranean basin, the coastal mean wind power density was calculated to be 96.06 W/m^2 in Agin-Elazig, Turkey [23]; 37, 29, and 25 W/m^2, respectively, in Iskenderun, Antakya, and Karats, Turkey [36]; 444.69 W/m^2 along the northern coasts of the Akrotiri Peninsula, Greece [28]; 109.31 W/m^2 in Tobruk, Libya [37]; and 112.70 W/m^2 in Cyprus [38]. At 80 m height, the mean wind power density was calculated to be 153.60 W/m^2 in Greece and 111.0 W/m^2 in south Turkey [7].

Conclusions

In conclusion, this paper highlights the importance of site-specific assessments in wind energy project planning. Stations with higher percentages in the moderate to optimal range, like PS (4.66 m/s, 79.78 W/m^2) and AQ (5.73 m/s, 169.40 W/m^2), are more suited for conventional wind turbine technologies. In contrast, sites like Arish, with a higher prevalence of lower wind speeds (3.91 m/s, 50.74 W/m^2), may require turbines designed for these conditions or alternative renewable energy approaches. The variability and range of wind power densities observed also highlight the need for tailored approaches to wind energy exploitation at each location, taking into account the specific wind characteristics of each site. According to the results obtained by the Weibull PDF, Abu Qir and Port Said showed promising characteristics for wind energy harnessing due to their concentrated and higher wind speed distributions. Conversely, Ras El-Tin and Arish, with their broader range of wind speeds, may require more robust and adaptable wind energy solutions. These findings are crucial for strategic planning and optimization of wind energy projects in the region, highlighting the need for tailored approaches based on the specific wind profiles of each location. Stations with higher Weibull shape

Table 11 Shape (k) and scale (c) parameters calculated along the Egyptian Mediterranean Coast

	MM		Alexandria		PS		Ar	
	k	c (m/s)	k	c (m/s)	k	c (m/s)	k	c (m/s)
[17]	1.34	4.86	1.34	4.01			1.15	1.84
[20]	1.14	4.29	1.49	4.36	1.71	4.77	2.39	4.56
[35]					1.86	4.4		
The present study	1.43	5.41	2.1	6.18	2.42	5.3	1.92	4.49

(k) and scale (c) parameters: AQ (2.308, 6.505 m/s) and PS (2.424, 5.335 m/s) are generally more favorable for wind energy development due to their potential for stable and high-yield energy production. Furthermore, based on the CDF analysis, AQ and MM were excellent candidates for wind energy projects since they frequently exhibited a suitable blend of moderate to high wind speeds. In contrast, Arish, with a propensity for lower wind speeds, might be less favorable for large-scale wind energy developments. The overall analysis shows that AQ and PS are potentially the most suitable locations for wind energy projects. However, the high variability at AQ site requires robust system designs to manage the fluctuating wind conditions. PS might be more suitable for projects prioritizing stability and consistency over maximum energy output. Due to its lowest wind power density, Arish may not be as appropriate for large-scale wind energy projects. Nevertheless, it might still be taken into consideration for smaller installations or in conjunction with other renewable energy sources. The different statistical indices used in this study reflected good model fitting, displaying the reliability of the Weibull distribution as a tool for preliminary wind resource assessment along the Egyptian Mediterranean Coast and facilitating accurate predictions of wind power availability.

For a comprehensive suitability assessment, it is recommended to integrate this analysis with additional factors such as geographical constraints, accessibility, environmental impact assessments, and economic considerations. Moreover, long-term data analysis and on-site assessments are crucial for making informed decisions about the development of wind energy projects.

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Author contributions
KT was instrumental in designing the study and leading the data collection efforts along the Egyptian Mediterranean Coast. KT also took the lead in interpreting the complex data gathered and spearheaded the drafting and revising of the manuscript to ensure it met high intellectual standards. ME played a crucial role in setting up the analysis framework and was in charge of acquiring data from the meteorological stations. ME's contributions extended to applying statistical methods effectively and assisting in the drafting and critical revision of the manuscript to refine its intellectual content. OI provided substantial support in the study's design and was responsible for the statistical analysis, utilizing the Weibull distribution to assess wind energy potential. OI was also a major contributor to writing the manuscript, managing literature searches, and ensuring accurate data representation throughout the document. TMG oversaw the scientific direction of the project and contributed to the conceptualization of the wind energy assessment framework. TMG's expertise was vital in the critical review and revision process of the manuscript, ensuring that the study's findings were robust and scientifically valid. All authors have read and provided their final approval of the manuscript, confirming that the work presented meets the necessary criteria and reflects their collective efforts.

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Availability of data and materials
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

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Not applicable.

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