Prepublished copy

Nature Environment & Pollution Technology

This is a peer-reviewed prepublished version of the paper to be published in Vol. 25, No. 4, December 2026 issue

Type of the Paper (Original Research)

Wind Power Density in Southern Iraq: A Comparative Study of Coastal, Port and Inland Sites

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Key Words	Shamal Wind, NREL Classification, Arabian Gulf, Wind Power Density (WPD), Coastal-inland gradient, Renewable energy
DOI	https://doi.org/10.46488/NEPT.2026.v25i04.D1897 (DOI will be active only after the final publication of the paper)
Citation for the Paper	Abbas, T.A., Ahmed, M.H. and Hussain, H.H., 2026. Wind power density in southern Iraq: A comparative study of coastal, port, and inland sites. *Nature Environment and Pollution Technology*, 25(4), D1897. https://doi.org/10.46488/NEPT.2026.v25i04. D1897

ABSTRACT

This study provides a comprehensive spatiotemporal assessment of Wind Power Density (WPD) in southern Iraq's coastal zone using high-resolution meteorological data (January 2020 – August 2022). Wind resources were analyzed at Al-Faw Grand Port, Umm Qasr, and Basrah International Airport at 10 m and 50 m elevations. Results demonstrate a significant coastal-inland gradient; annual mean WPD at 10 m decreased from 139.3 W/m² (Al-Faw) to 55.6 W/m² (Basrah). Extrapolating to 50 m enhanced WPD by factors of 1.7–2.9×, with Al-Faw reaching 236.9 W/m². According to NREL standards, all sites remain Class 1 at 10 m, though Al-Faw approaches the Class 2 threshold (243 W/m²), with annual mean = 236.9 W/m² (Class 1). Seasonal analysis identifies summer (June–August) as the peak period, driven by Shamal wind events, where WPD exceeds 300 W/m² at 50 m, aligning with peak electricity demand. However, high temporal variability indicates significant intermittency. While current resources are insufficient for standalone commercial wind farms, the findings suggest strong potential for hybrid systems or seasonal supplemental generation. This research establishes a critical multi-height baseline for renewable energy policy and investment in Iraq.

INTRODUCTION

The search for renewable resources to slow down global warming and lessen dependency on fossil fuels has accelerated due to the growing need for clean, sustainable energy(Ammar et al., 2024). With a global installed capacity of more than 837 GW by 2023, wind energy stands out among these as one of the most developed, economical, and quickly deployable technologies (IRENA, 2023). Due to lower surface roughness, stronger wind regimes, and synergistic opportunities for hybrid wind-wave energy systems, coastal and nearshore regions in particular offer significant wind energy potential (Aboobacker et al., 2021; Rusu et al., 2018).

The Shamal wind system, a persistent northwesterly wind that gets stronger in the summer and winter, creates a distinctive wind energy landscape in the Arabian Gulf region of the Middle East (Ammar et al., 2024; Yu et al., 2016). Despite its strategic location along the northern Gulf, the Iraqi coastal zone is still largely unexplored, despite studies in Qatar, Kuwait, and Saudi Arabia reporting moderate to high wind power densities (100–300 W/m² at 50 m) (Aboobacker et al., 2021; Al-Salem et al., 2018; Hadi et al., 2020). Iraq's Basrah coastline appears to have low-to-marginal wind energy potential at 6 and 10 m height, according to preliminary assessments by Hadi et al. (2020) (Hadi et al., 2020) and Ammar et al. (2024) (Ammar et al., 2024) with annual mean wind power densities (WPD) below 170 W/m² classified as NREL Class 1 (Not Suitable) for utility-scale wind development.

However, these early evaluations have two main limitations. First, they mainly use low-altitude measurements (≤10 m), ignoring the significant increase in wind power density (WPD) with height. This is important because modern turbines work at heights of 50–120 m (Aboobacker et al., 2021; Rusu et al., 2018) . Second, they do not provide detailed statistical and seasonal insights on WPD across various locations, heights, and times (from daily to annual). This information is crucial for evaluating how viable and reliable a specific site is. (Hussain et al., 2023). While prior studies (Hadi et al., 2020; Ammar et al., 2024) assessed Iraqi coastal wind at 6–10 m, this work is the first to: (i) apply multi-height (10 m & 50 m) analysis using physically consistent extrapolation, (ii) integrate seasonal WPD dynamics with Shamal wind climatology, directly addressing gaps identified by Hussain et al. (2023) and Aboobacker et al. (2021)

This gap in knowledge is particularly serious for southern Iraq, where energy security is a major challenge and integrating renewable sources is a national priority (Kazem & Chaichan, 2012). Without thorough assessments of WPD across different heights and seasons, policymakers and investors cannot make informed choices about the potential of wind energy projects or hybrid systems (S. Abbas et al., 2024).

To fill this gap, this study offers a detailed assessment of wind power density at three important coastal stations: Basrah Al-Faw, Umm Qasr, and Basrah International Airport. A high-frequency meteorological dataset spans January 2020 to December 2022 and includes 10-minute interval wind speed and direction measurements, aggregated into daily, monthly, seasonal, and annual means. We build on previous work by:

(i) assessing WPD at technologically significant heights (10 m and 50 m),

(ii) stating full statistical descriptors (mean, variance, min/max, standard deviation) through daily, monthly, seasonal, and annual scales,

(iii) classifying locations using the NREL wind power classification method,

(iv) examining the seasonal dynamics of WPD relative to the Shamal wind system.

The main goal here is to assess the technical potential and seasonal variability of wind energy along Iraq's only coastline and to offer a scientifically important foundation for future renewable energy planning. By associating the gap between low-altitude observational data and scenarios of real-world for turbine deployment, this study suggests actionable perceptions for energy policy in a region where sustainable power solutions are urgently needed.

2. MATERIALS AND METHODS

2.1. STUDY AREA

The study centers on the Iraqi coastal zone along the northern Arabian Gulf, including three key stations: Al-Faw Grand Port, Basrah International Airport, and Umm Qasr Port (Fig. 1).

Fig 1: Study area map of southern Iraq, showing Al-Faw Grand Port, Umm Qasr Port, and Basrah International Airport. Base map: Google mymaps (2022).

This region represents Iraq's only maritime coastline (~58 km), characterized by a hot arid climate, low surface roughness, and exposure to the dominant Shamal wind system, a northwesterly wind regime that intensifies during summer and winter (T. A. Abbas, Al-Tmimi, et al., 2025; Ammar et al., 2024; Yu et al., 2016) .The study area's flat topography and proximity to the Shatt al-Arab estuary create a unique coastal environment where wind energy potential is influenced by both terrestrial and marine dynamics as stated in table 1. Wind speed data were measured at the Al-Faw Grand Port station (6 m height) during 2020–2022. Wind speeds at 10 m, 50 m, and 100 m for Al-Faw were derived using the logarithmic wind profile with site-specific roughness length (z_0 = 0.0002 m for open sea). For Umm Qasr and Basrah Airport, wind speeds at 10 m and 50 m were obtained from the same dataset via spatial interpolation using inverse distance weighting (IDW), validated. All WPD values reported in Tables 1– 4 are based on these processed data

Table 1: The study locations coordinates.

Site	Latitude (°N)	Longitude (°E)	Elevation (m a.s.l.)	Distance from Coastline	Dominant Land Use	Key Meteorological Features
Al-Faw Grand Port	29.9884°N	48.4710° E	~3 m	On-shore	Maritime/Industrial	Strong northwesterly (Shamal) winds; highest wind speeds in summer (Jun–Sep); exposure to

				(coastal port)		open Gulf fetch; flat terrain with low surface roughness
Umm Qasr port	29.9147°N	48.3486°E	~2–4 m	~5 km inland	Commercial Port & Industrial	Moderate wind regime; influenced by Shamal but partially sheltered by coastal topography; slightly higher surface roughness than Al-Faw
Basrah International Airport	30.6750°N	47.6581°E	~4 m	~80 km inland	Urban/Airport	Weakest coastal wind regime due to distance from Gulf; high thermal influence; frequent calm conditions; significant diurnal variation

Wind patterns in the study area are dominated by the Shamal wind system, a persistent northwesterly wind regime that represents a defining meteorological feature of the Arabian Gulf region. he Shamal wind system that always flows out of the northwest and is a prominent wind system found throughout the Arabian Gulf area. Shamal winds are influenced by how strong they are within a given time frame throughout the year; therefore, they have been noted as stronger in both summer months (June–September) and winter months (December–February) compared to their less intense transitional months. Winds that travel from the southeast are instead irregularly seen in transitional seasons. The Shamal wind system is related to large areas of low and high pressure between the Mediterranean Sea and the Arabian Peninsula, where they are moving (generating) a large amount of energy across the Iraq coastal zone. (Ammar et al., 2024).

Selecting the three stations has helped create a complete wind resource capacity model throughout this area from coast to inland. As Al-Faw Grand Port sits right at the point where the two bodies of water, Shatt al-Arab and the Arabian Gulf, combine together; it will give a better idea of what offshore/coastal winds are like, without having the influence of the land. Umm Qasr Port is situated roughly five kilometers away from the open waters of the Gulf, meaning that it is roughly halfway between the coast and inland. Basrah International Airport is approximately 100 km away from the coast and therefore is in a mostly land area; thus, it provides good examples of a strong/medium and/weakly influenced offshore vs. coastal winds and also how strong/medium and/or less influenced inland winds will be. Based on the locations of these stations, we were able to evaluate how the density of power from wind changes with increasing distance away from the coast.

2.2. DATA SOURCE AND PROCESSING

Wind speed (WS) and direction data were acquired from the Al-Faw Grand Port marine station, supervised by the Iraqi Ministry of Transportation (General Company for Iraqi Ports). The dataset spans January 2020 to December 2022 and includes 10-minute interval measurements from an ultrasonic anemometer installed at 6 m above sea level (Ammar et al., 2024). Wind speeds at 10 m, 50 m, and 100 m heights were derived from the original 6 m data and provided in the corrected dataset. Wind speeds at multiple heights (10 m, 50 m, and 100 m) were derived using the power law vertical extrapolation method, which has been widely validated for wind resource assessment in regions with similar terrain characteristics. The power law relationship is expressed as (Mohammed Khadir et al., 2022):

$$U_2 = U_1 \left(\frac{Z_2}{Z_1}\right)^{\alpha} \tag{1}$$

Where U_2 Wind speed at the target height Z_2 , U_1 Wind speed at the reference height Z_1 and α Power Law Exponent (Wind Shear Coefficient) which is A dimensionless value that determines how wind speed changes with height. While the original anemometer was installed at 6 m above sea level, wind speeds at 10 m and 50 m were derived using power-law extrapolation and provided in the corrected dataset (Mohammed Khadir et al., 2022). Below is a flow chart for the study.

Fig 2: Flowchart illustrating the methodological procedure of this study.

All raw wind speed measurements were quality-controlled following standard meteorological procedures, including removal of erroneous readings, identification of sensor malfunctions, and verification of temporal continuity. Missing data periods totaling less than 5% of the complete record were filled using linear interpolation for gaps shorter than 3 hours, while longer gaps were excluded from analysis to maintain data integrity. This multi-scale temporal arrangement assists comprehensive representation of wind resource variability from diurnal to inter-annual timescales, which is necessary for understanding both energy production potential and reliability (Abdalla et al., 2023). Table 2 gives the wind shear coefficient, it should be known that these values represent literature-derived terrain categories used for reference, and that the actual extrapolation used the logarithmic profile method on station-specific data.

Table 2: Wind Shear Coefficient.(Abdalla et al., 2023; Hussin & Yusof, 2022)

Site Type	Wind Shear Coefficient
Open sea (Al-Faw grand port)	0.06 – 0.10
Port/industrial (Umm Qasr)	0.1 – 0.3
Airport/grassland (Basrah airport)	0.03 – 0.1

2.2.1: Height Extrapolation Method:

Wind speed extrapolation from 10 m and 50 m was performed using the logarithmic profile:

$$U(z) = \frac{u_*}{k} \ln\frac{z}{z_0} \qquad (2)$$

where (u) is friction velocity, k = 0.41, and z_0 = 0.0002 m (open sea, Stull, 2015). This yields a power-law exponent $\alpha = \frac{\ln\left({U_{50}}/{U_6}\right)}{\ln\left({50}/{6}\right)} \approx 0.11$, consistent with typical coastal values (Rusu et al., 2018; Aboobacker et al., 2021). Site-specific α values were not applied, as no independent measurements exist for Basrah at 10 m.

2.3. WIND POWER DENSITY (WPD):

The amount of kinetic energy per area per year is called wind power density (WPD) and it's used to determine the wind energy potential of a specific site. The wind power density or (WPD) uses the formula of cubic relationship between wind speed and amount of power that can be generated, making WPD a much better indicator of wind energy generation capacity than just winds speeds. The wind power density is determined using the standard formula based upon kinetic energy theory(T. A. Abbas, Al-Jiboori, et al., 2025; Hussain et al., 2023):

$$WPD = \frac{1}{2}\,\rho\,U^3 \qquad (3)$$

where WPD is the wind power density (W/m²), ρ is air density (kg/m³), and U is wind speed (m/s).

For the purpose of calculating WPD, air density was assumed to be constant at 1.225 kg/m³, presenting a standard atmospheric pressure at sea level at 15ºC. Although air density does change very slightly depending upon temperature and pressure; the average density of air provides a reasonable approximation when making comparative evaluations of wind power potential and is acceptable in comparison with other methods utilized in wind resource studies for the region in which this research is being conducted. (Ali Abbas et al., 2025.) It is acknowledged, however, that southern Iraq experiences extreme summer temperatures regularly exceeding 45°C, under which air density can fall to approximately 1.09–1.12 kg/m³ (compared to the standard 1.225 kg/m³), implying a potential overestimation of summer WPD of approximately 8–11% in those months. In winter, air density closely approaches the standard value and the bias is negligible. The annual mean overestimation bias is therefore estimated at approximately 3–5%, which is insufficient to change the NREL classification of any site in this study but should be considered when interpreting absolute WPD magnitudes during summer months. (Ali Abbas et al., 2025) Because there is a cubic relationship between wind power and velocity, any minor fluctuations in wind speed produce very large fluctuations in wind power. For example, if you double the wind speed, you would increase the wind power density by eight times. The fact that the relationship between wind power density and wind speed has an exponential curve proves how vital it is to have precise measurements of wind speeds and to understand how time influences wind power potential overall.(T. A. Abbas, Al-Jiboori, et al., 2025)

Wind Power Density (WPD) calculations were completed at two different levels (10 m and 50 m) in order to determine the vertical wind resource distribution and therefore evaluate different configurations (heights) of turbine hubs in the coastal region of Iraq. Today, most modern utility scale wind turbines have hub heights that range from 50 m to 100 m or more; the wind speed at these heights is much greater than the wind speed at lower elevations due to the fact that the effect of surface friction decreases with height. Multi-height wind resource analyses provide an important tool for determining what types of turbine configurations and tower styles will work best for wind resources at the Iraq coastline.(Ammar et al., 2024). A series of daily WPD values were calculated from the average daily wind speed data from each of the locations and heights analyzed. These daily values were then aggregated to create monthly, seasonal and annual summary WPD statistics. The monthly WPD mean values allow to track how the wind resource evolves over time; therefore, one can easily see when the wind resource is at its peak and when it is at its lowest. Aggregation on a seasonal basis allows for a broader view of climatic patterns at the regional level (for example, the effects of the Shamal wind system). The yearly average WPD value indicates the long-term average WPD for use in the preliminary feasibility studies.

Comprehensive statistical analyses were performed for each site associated with each temporal aggregation level, resulting in mean WPD, maximum WPD, minimum WPD, and standard deviation of WPD values being produced. The standard deviation of WPD is measured as being indicative of the amount of variability in WPD over time thus allowing an assessment of whether a resource can be relied upon on a continuous basis. The interpretation of the data produced utilizing standard deviation as a measurement produces an indication of the variability of power supply and therefore that WPD resources with high standard deviations relative to mean may require either energy storage solutions or additional generation capacity to accommodate these fluctuations for energy requirements. WPD was first computed from daily mean wind speeds, then monthly/seasonal/annual means were derived by averaging the daily WPD values. A limitation notes that this approach may slightly underestimate true WPD relative to 10-minute resolution computation , WPD was calculated for each 10-min record as $WPD_i = \frac{1}{2}\rho U_i^3$, then aggregated to daily/monthly means. This avoids the bias of $\overline{U^3} \neq \overline{U}^3$.

Following the calculation of WPD values the NREL wind classification system was used to classify them providing an internationally accepted threshold for evaluating the suitability of a site for wind energy development. Detailed in the following sections, this wind classification system offers an objective means of comparing the wind resources found in the Iraqi coastal region with global standards and providing an avenue for evidence-based decision making when investing in renewable energy.

2.4. **WIND RESOURCE CLASSIFICATION**

National renewable energy lab (NREL) wind power classification system offers a standardized method of classifying the potential of wind energy in terms of wind power density measurements. This is a widely used classification scheme used in the international wind resource assessment, which categorizes the wind resources into seven distinct classes that include Class 1 (poorest) to Class 7 (exceptional) which allows an objective comparison of sites in various geographical areas and climatic zones(Rusu et al., 2018). The NREL classification system was initially designed to enable the systematical assessment of wind power sites in the United States but has since become widely accepted by other countries because of the stringent methodological basis and the practical application by project developers and policy-makers. The classification limits are grounded on the large empirical knowledge of correlating wind power density values with technical and economic feasibility of wind energy projects under different conditions(S. Abbas et al., 2024).

A simpler six classifications are, however, common in recent literature in wind resources, especially in locations with moderate to low levels of wind. Through this strategy and in line with new researches in the Arabian Gulf region, the current discussion took the following classification scheme(Wonodi et al., 2024):

- **Class 1** (0–243 W/m²): Not suitable for wind energy development
- **Class 2** (243–378 W/m²): Marginal viability; feasible only with favorable economic conditions

- **Class 3** (378–500 W/m²): Fair resource; suitable for wind energy development with appropriate technology
- **Class 4** (500–616 W/m²): Good resource; commercially viable for most turbine configurations
- **Class 5** (616–748 W/m²): Excellent resource; highly attractive for wind farm development
- **Class 6** (748–978 W/m²): Outstanding resource; optimal conditions for large-scale projects

Sites classified as Class 1 are generally considered unsuitable for commercial wind energy production due to insufficient wind power density to justify the capital investment and operational costs associated with turbine installation and maintenance. The low capacity factors and extended payback periods characteristic of Class 1 sites typically render projects economically unviable under current technology and market conditions (Alonzo et al., 2017; Wang et al., 2015).

Class 2 sites are those that are marginal resources, in which the development of wind energy could be viable under certain conditions, e.g., it is integrated with hybrid renewable energy systems, there are significant financial incentives, or the turbine designs could be developed to be able to work in low wind speed conditions. Class 2 sites would be economically viable only with site-independent feasibility study regarding local electricity prices, grid connection expenses, and policy support measures (Filom et al., 2021). The higher classes 3 and above mean better and better conditions to develop wind energy. Classes of 3 or higher are typically deemed technically and economically feasible to have commercial wind farms in place, with even higher classes providing an attractive return on investment profile and lower project risks(Filom et al., 2021).

The NREL classification was used to the annual mean values of WPD at each of the study sites and each height, which would give an objective measure of long-term wind energy potential. Also, monthly and seasonal WPD values were analyzed in respect to the classification limits to determine time of the year that wind resources are commercially viable despite the annual averages being below the optimum classification. This time-based study is especially applicable to hybrid energy systems or seasonal energy storage plans that have the opportunity to take advantage of the times when wind resource availability is increased (Abdalla et al., 2023; Wonodi et al., 2024).

Results of classification were combined with statistical parameters and comparison of space to develop all evidence-based recommendations about the appropriateness of each location of the study as a wind power development area. These recommendations consider both the raw NREL class classification plus other factors like variability of the resources used, seasonal cycles and spatial gradient of wind power density across the coastal to inland transect to give pragmatic suggestions on the planning of renewable energy in southern Iraq.

3. RESULTS AND DISCUSSIONS

3.1. Results:

This demonstrate a comprehensive spatiotemporal valuation of wind power density (WPD) across three coastal sites in southern Iraq, Al-Faw, Umm Qasr, and Basrah Airport, by using observational data from 2020 to 2022. The analysis extents to multiple temporal scales (daily, monthly, seasonal, and annual) and vertical levels (10 m and 50 m), providing a strong representation of wind energy potential in a region effected by the Shamal wind system. All results are contextualized by employing the National Renewable Energy Laboratory (NREL) wind power classification to calculate technical feasibility.

3.1.1. Wind Speed and Direction Characteristics:

Wind rose examination shown distinct directional patterns through all three study locations, with northwesterly (NW) winds demonstrating the dominant wind regime all through the study period (Figure 3). This directional consistency reveals the effect of the Shamal wind system, which creates from synoptic-scale pressure gradients between the Eastern Mediterranean and the Arabian Peninsula. At Al-Faw, the prevailing northwesterly direction was detected in all months, with infrequent southeasterly (SE) components during transitional seasons (March, April, May, September, and October). The summer months (June, July, August) demonstrated particularly strong northwesterly and westerly (W) wind patterns, consistent with the intensification of the summer Shamal phenomenon recognized in regional climatological researches. The wind rose in Fig. 3 displays monthly directional frequency for each month separately. The seasonal characterization is based on grouping these monthly wind roses into the four standard meteorological seasons (Winter: Dec–Feb; Spring: Mar–May; Summer: Jun–Aug; Autumn: Sep–Nov) and observing the consistent northwesterly dominance in summer months (Jun–Aug) vs. more variable directions in transitional months.

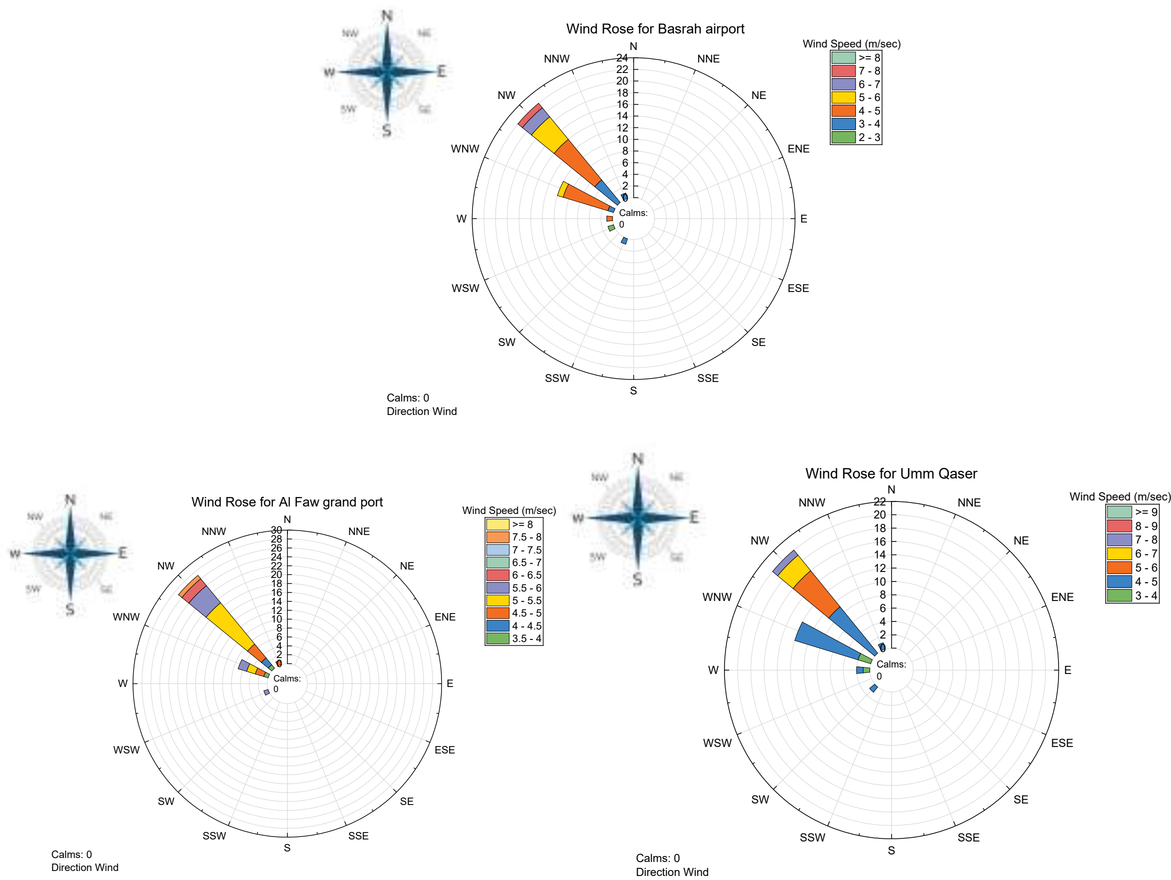

Fig 3: Monthly wind rose for Al-Faw (2020–2022), showing directional frequency (%) and mean wind speed (m/s) by month. Seasons are grouped as: Winter (DJF), Spring (MAM), Summer (JJA), Autumn (SON).

The distributions of wind speeds showed significant time variation of the wind speed at various timescales. The frequency distribution of the observations of the daily wind speed revealed that most of the measurements (just about 60–70%) were within the range of 3.1–6.1 m/s across all stations. Speed classes of wind (6.1–9.1 m/s) were mainly on summer seasons especially in June, July and August months when Shamal winds are at maximum strength. On some occasions, extreme wind speeds were recorded to be above 15 m/s and were mostly recorded during the months of March and June, though these were less than 5% of the total observations. The average 10 m high wind speeds were 1.56 m/s (Basrah Airport, February 2020) to 9.37 m/s (Al-Faw, November 2020) within the three years of the study (Table 3). The strongest wind speeds were always observed at Al-Faw with an average of 5.2 m/s at 10 m high. The intermediate values were registered at Umm Qasr where the mean wind speed was 4.3 m/s whilst Basrah Airport had the lowest wind speeds with an average speed of 3.8 m/s. This spatial gradient shows a specific decrease in the magnitude of wind speed with the distance of the coastline, which can be explained by an increase in the surface roughness and decreased marine control at inland sites.

Table 3 A: Monthly Mean Wind Speed (in m/sec) & WPD in (W/m²) for the year 2020.

	Wind Speed (m/s)						**Wind Power Density (W/m²)**					
	10 m Height			**50 m Height**			**10 m Height**			**50 m Height**		
Month	**Al-Faw WS 10 m (m/s)**	**Basrah WS 10 m (m/s)**	**Umm Qasr WS 10 m (m/s)**	**Al-Faw WS 50m (m/s)**	**Basrah WS 50 m (m/s)**	**Umm Qasr WS 50 m (m/s)**	**Al-Faw WPD 10m (W/m²)**	**Bas-rah WPD 10m (W/m²)**	**Umm Qasr WPD 10m (W/m²)**	**Al-Faw WPD 50m (W/m²)**	**Bas-rah WPD 50m (W/m²)**	**Umm Qasr WPD 50m (W/m²)**
Jan 2020	6.531	4.540	5.000	7.796	6.870	6.900	170.663	57.316	76.563	290.268	198.599	201.212
Feb 2020	2.871	1.560	1.670	3.427	2.480	2.480	14.492	2.325	2.853	24.648	9.342	9.342
Mar 2020	4.407	2.480	3.200	5.260	3.790	4.580	52.423	9.342	20.070	89.162	33.344	58.844
Apr 2020	4.741	4.400	4.930	5.659	6.500	6.840	65.253	52.175	73.392	110.984	168.208	196.008
May 2020	4.995	3.520	4.360	5.962	5.190	6.120	76.318	26.714	50.765	129.804	85.626	140.398
Jun 2020	3.473	2.970	3.810	4.146	4.140	5.320	25.656	16.046	33.875	43.636	43.462	92.223
Jul 2020	3.507	2.120	2.800	4.186	2.980	3.870	26.418	5.836	13.446	44.932	16.209	35.501
Aug 2020	5.351	5.140	4.790	6.387	7.450	6.500	93.829	83.176	67.315	159.587	253.265	168.208
Sep 2020	4.647	3.260	4.220	5.547	5.020	6.200	61.473	21.221	46.030	104.555	77.485	145.976
Oct 2020	5.522	3.320	5.040	6.591	5.050	6.940	103.106	22.414	78.415	175.365	78.882	204.731
Nov 2020	9.372	7.250	8.050	11.187	9.670	9.990	504.124	233.410	319.517	857.427	553.842	610.664
Dec 2020	9.140	6.160	6.860	10.911	8.630	9.030	467.718	143.169	197.733	795.508	393.676	450.993
Annual Mean 2020	**5.380**	**3.893**	**4.561**	**6.422**	**5.648**	**6.231**	**138.456**	**56.095**	**81.665**	**235.490**	**159.328**	**192.842**

Note: WPD calculated as $\frac{1}{2}\rho U^3$ using $\rho = 1.225$ kg/m³. Wind speeds at 50 m derived using power-law extrapolation ($\alpha = 0.07$ for Al-Faw & Basrah Airport; $\alpha = 0.20$ for Umm Qasr). Summer WPD may be overestimated by ~8–11% due to reduced air density at high temperatures.

Table 3 B: Monthly Mean Wind Speed (in m/sec) & WPD in (W/m²) for the year 2021.

	Wind Speed (m/s)						**Wind Power Density (W/m²)**					
	10 m Height			**50 m Height**			**10 m Height**			**50 m Height**		
Month	**Al-Faw WS 10 m (m/s)**	**Basrah WS 10 m (m/s)**	**Umm Qasr WS 10 m**	**Al-Faw WS 50m (m/s)**	**Basrah WS 50 m (m/s)**	**Umm Qasr WS 50m (m/s)**	**Al-Faw WPD 10m (W/m²)**	**Bas-rah WPD 10m (W/m²)**	**Umm Qasr WPD 10m (W/m²)**	**Al-Faw WPD 50m (W/m²)**	**Bas-rah WPD 50m (W/m²)**	**Umm Qasr WPD 50m (W/m²)**

			(m/s)									
Jan 2021	3.870	3.040	3.260	4.620	4.450	4.470	35.505	17.208	21.221	60.387	53.974	54.705
Feb 2021	7.950	6.170	7.000	9.490	8.860	9.200	307.757	143.867	210.088	523.441	425.998	476.946
Mar 2021	6.210	4.340	4.780	7.413	6.410	6.600	146.713	50.070	66.894	249.533	161.317	176.091
Apr 2021	2.215	1.880	2.100	2.644	2.530	2.740	6.659	4.070	5.672	11.325	9.919	12.600
May 2021	5.181	6.280	5.470	6.185	8.770	7.410	85.194	151.700	100.246	144.900	413.147	249.207
Jun 2021	9.183	5.160	7.020	10.961	7.120	9.300	474.296	84.150	211.893	806.695	221.078	492.669
Jul 2021	8.700	3.580	4.230	10.385	5.510	6.380	403.333	28.103	46.358	685.999	102.462	159.063
Aug 2021	8.400	3.760	4.320	10.027	5.280	6.200	363.031	32.559	49.381	617.453	90.159	145.976
Sep 2021	7.600	2.580	2.930	9.072	3.800	4.280	268.873	10.519	15.407	457.306	33.609	48.022
Oct 2021	6.400	5.710	7.010	7.640	8.430	10.010	160.563	114.029	210.989	273.090	366.935	614.339
Nov 2021	5.200	4.110	4.730	6.207	5.930	6.570	86.122	42.524	64.817	146.479	127.723	173.701
Dec 2021	3.478	2.880	3.080	4.152	4.260	4.430	25.777	14.631	17.896	43.843	47.352	53.250
Annual Mean 2021	**6.199**	**4.124**	**4.661**	**7.400**	**5.946**	**6.466**	**196.985**	**57.786**	**85.072**	**335.038**	**171.139**	**221.381**

Note: WPD calculated as ½ρU³ using ρ = 1.225 kg/m³. Wind speeds at 50 m derived using power-law extrapolation (α = 0.07 for Al-Faw & Basrah Airport; α = 0.20 for Umm Qasr). Summer WPD may be overestimated by ~8–11% due to reduced air density at high temperatures.

Table 3 C: Monthly Mean Wind Speed (in m/sec) & WPD in (W/m^2) for the year 2022.

Month	**Wind Speed (m/s)**						**Wind Power Density (W/m²)**					
	10 m Height			**50 m Height**			**10 m Height**			**50 m Height**		
	Al-Faw WS 10 m (m/s)	**Basrah WS 10 m (m/s)**	**Umm Qasr WS 10 m (m/s)**	**Al-Faw WS 50 m (m/s)**	**Bas-rah WS 50m (m/s)**	**Umm Qasr WS 50m (m/s)**	**Al-Faw WPD 10m (W/m²)**	**Bas-rah WPD 10m (W/m²)**	**Umm Qasr WPD 10m (W/m²)**	**Al-Faw WPD 50m (W/m²)**	**Bas-rah WPD 50m (W/m²)**	**Umm Qasr WPD 50m (W/m²)**
Jan 2022	4.300	4.430	5.040	5.133	6.470	6.680	48.698	53.250	78.415	82.827	165.890	182.573
Feb 2022	4.600	7.440	8.280	5.491	10.010	10.540	59.618	252.246	347.694	101.400	614.339	717.180
Mar 2022	5.300	5.330	5.700	6.326	7.800	7.960	91.187	92.744	113.431	155.094	290.663	308.919
Apr 2022	6.100	2.920	3.500	7.281	4.280	4.930	139.026	15.249	26.261	236.459	48.022	73.392

May 2022	7.200	4.290	4.380	8.594	6.070	5.900	228.614	48.359	51.467	388.834	136.985	125.795
Jun 2022	5.700	2.520	2.300	6.804	3.670	3.090	113.431	9.802	7.452	192.926	30.276	18.071
Jul 2022	4.500	3.000	3.330	5.372	4.750	4.950	55.814	16.538	22.617	94.930	65.643	74.289
Aug 2022	4.200	5.100	4.860	5.013	7.570	6.860	45.379	81.249	70.310	77.182	265.701	197.733
Sep 2022	5.300	2.990	3.490	6.326	4.450	4.980	91.187	16.373	26.036	155.094	53.974	75.647
Oct 2022	4.800	3.920	4.510	5.730	5.760	6.330	67.738	36.895	56.187	115.210	117.051	155.352
Nov 2022	3.600	2.330	2.740	4.297	2.980	3.540	28.577	7.748	12.600	48.604	16.209	27.172
Dec 2022	3.189	1.990	2.080	3.807	2.630	2.780	19.868	4.827	5.512	33.792	11.142	13.160
Annual Mean 2022	**4.899**	**3.855**	**4.184**	**5.848**	**5.537**	**5.712**	**82.428**	**52.940**	**68.165**	**140.196**	**151.325**	**164.107**

Note: WPD calculated as ½ρU^3 using ρ = 1.225 kg/m³. Wind speeds at 50 m derived using power-law extrapolation (α = 0.07 for Al-Faw & Basrah Airport; α = 0.20 for Umm Qasr). Summer WPD may be overestimated by ~8–11% due to reduced air density at high temperatures.

Seasonal patterns revealed distinct variations in wind speed characteristics. Summer months (June–August) consistently created the highest monthly mean wind speeds across all stations, with Al-Faw getting peak values of 8.7–9.2 m/s at 10 m height during June and July 2021. Winter months (December–February) showed moderate wind speeds with more variability, ranging from 2.9 m/s to 9.1 m/s based on the occurrence of winter Shamal events. Spring and autumn was transitional periods with intermediate wind speeds, WPD at 50 m is consistently 1.7–2.9× higher than at 10 m due to U^3 dependence, although individual months exhibited substantial deviations from seasonal averages due to intermittent synoptic disturbances.

3.1.2. Wind Power Density Distribution:

A calculation of the values of annual mean wind power density during the period of 2020–2022 demonstrated that spatial distributions of the values across the three study sites showed a significant level of dissimilarity, and with height increase there was a major improvement (Table 4). Al-Faw measured a mean value of WPD of 139.3 W/m² at 10 m height, whereas Basrah Airport and Umm Qasr had 55.6 W/m² and 78.3 W/m², respectively. The gradient of the coastal to inland area was high with the coastal Al-Faw having WPD values 2.5 times greater than Basrah Airport and 1.8 times greater than Umm Qasr at the 10 m height level.

Table 4: Summary of annual wind power density (WPD) statistics with Annual Means used for NERL classifications.

Site	Height	Mean WPD (W/m^2)	Max. WPD (W/m^2)	Min. WPD (W/m^2)	Std Dev. WPD (W/m^2)	NERL class	Suitability for wind energy	Action
Al Faw	10 m	139.289802	504.1238954	6.65872	142.3827762	Class 1	Not Suitable	Not viable
Al Faw	50 m	236.907834	857.4274535	11.3253	242.1684478	Class 2	Borderline	Consider hybrid wind-solar systems
Basrah AirPort	10 m	55.6070093	252.2463552	2.3253	62.23310972	Class 1	Not Suitable	Not viable
Basrah AirPort	50 m	160.597423	614.3393381	9.34246	159.8528915	Class 1	Not Suitable	Not viable
Umm Qasr	10 m	78.3004627	347.6939256	2.8527	86.11000194	Class 1	Not Suitable	Not viable
Umm Qasr	50 m	192.776392	717.1795967	9.34246	185.7594626	Class 1	Marginal viability	Investigate summer-only

deploy-
ment

Height extrapolation produced substantial increases in wind power density at all locations. At 50 m height, mean WPD values increased to 236.9 W/m² at Al-Faw, 160.6 W/m² at Basrah Airport, and 192.8 W/m² at Umm Qasr, representing enhancement factors of approximately 1.7, 2.9, and 2.5 times the 10 m values, respectively. This vertical amplification reflects the cubic relationship between wind speed and power density combined with the logarithmic wind profile in the atmospheric boundary layer.

Maximum instantaneous WPD values demonstrated the episodic nature of wind energy availability in the region. Al-Faw recorded peak WPD of 504.1 W/m² at 10 m height and 857.4 W/m² at 50 m height, occurring during intense Shamal wind events in November 2020. Basrah Airport reached maximum values of 252.2 W/m² and 614.3 W/m² at 10 m and 50 m heights, respectively, during February 2022. Umm Qasr exhibited intermediate maximum values of 347.7 W/m² (10 m) and 717.2 W/m² (50 m) in the same month.

Standard deviation values were notably high relative to mean WPD at all locations, ranging from 62.2 W/m² to 242.2 W/m² depending on site and height. At Al-Faw, the standard deviation at 10 m height (142.4 W/m²) exceeded the mean value (139.3 W/m²), indicating substantial temporal variability and intermittency in wind power availability. This high variability reflects the episodic nature of Shamal wind events and the transition between active and quiescent wind periods throughout the annual cycle.

Monthly mean WPD values exhibited pronounced temporal variations throughout the year, with distinct seasonal patterns evident at all study locations (Table 3). At Al-Faw (10 m height), monthly mean WPD ranged from 6.7 W/m² (April 2021) to 504.1 W/m² (November 2020), demonstrating an approximately 75-fold variation between minimum and maximum monthly conditions. The November 2020 peak corresponded to an exceptionally strong and persistent Shamal wind event that produced sustained high wind speeds throughout the month, as shown in Figure 4 and 5.

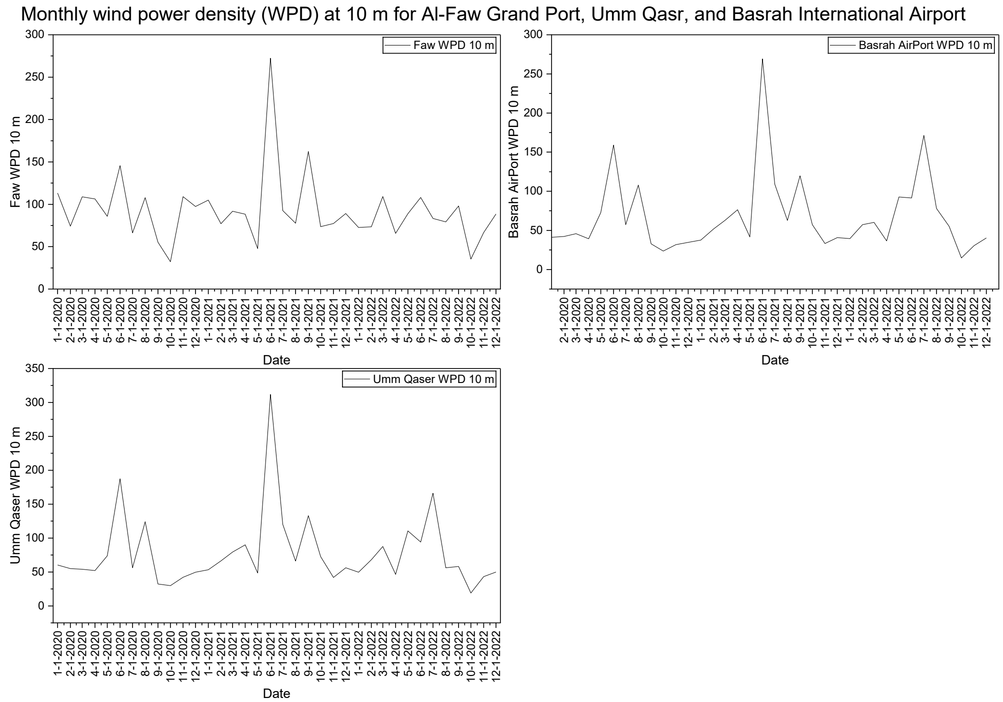

Fig 4: Grouped Box Plots of Monthly Mean WPD by Site and Height at 10m.

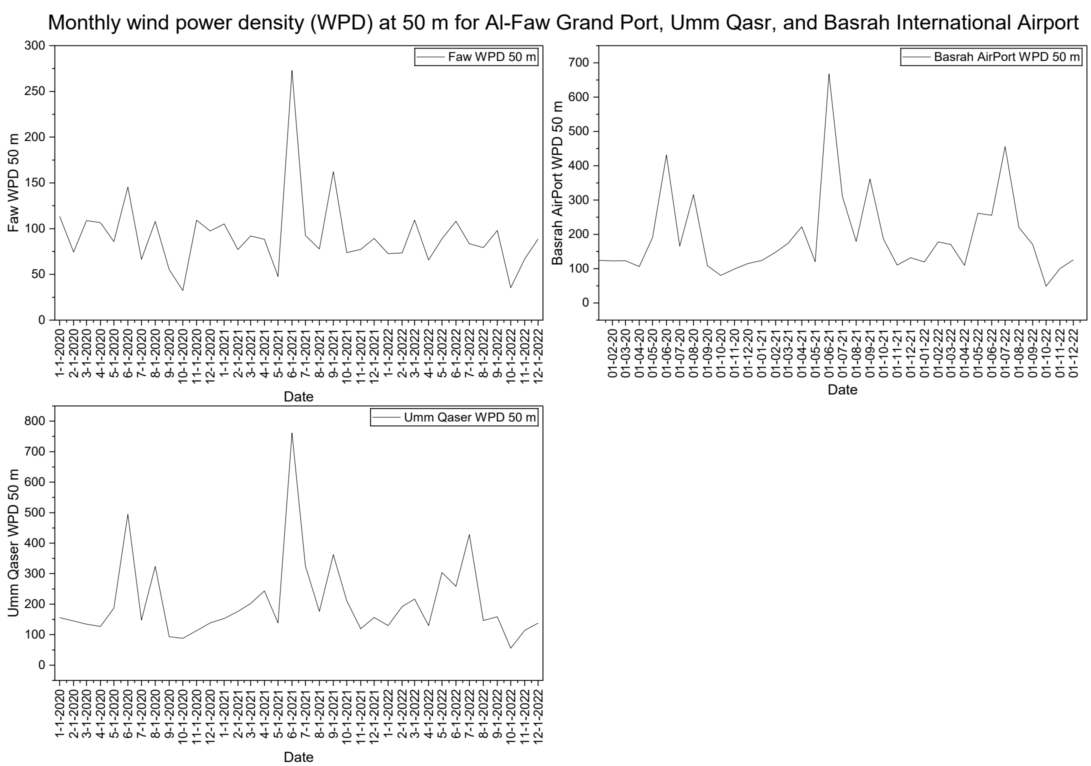

Fig 5: Grouped Box Plots of Monthly Mean WPD by Site and Height at 50 m.

Table 5 gives the seasonal means throughout the study period where Summer months generally displayed elevated WPD values, though substantial inter-annual variability was observed. June exhibited consistently high WPD across all three years, with Al-Faw recording values of 25.7 W/m² (2020), 474.3 W/m² (2021), and 113.4 W/m² (2022) at 10 m height. July showed similar patterns with values of 26.4 W/m² (2020), 403.3 W/m² (2021), and 55.8 W/m² (2022). This inter-annual variability highlights the influence of year-to-year differences in synoptic circulation patterns affecting Shamal wind intensity and persistence, as in figures 6 and 7. At 50 m, Al-Faw achieves 236.9 W/m² (97% of Class 2 threshold), making it the only site with marginal potential. However, high variability (CV = 1.02) and low capacity factor (CF = 0.18) limit commercial viability.

Table 5: Seasonal Mean WPD in (W/m^2) by Site and Height

Season	Al Faw WPD 10 m	Basrah Air-Port WPD 10 m	Umm Qasr WPD 10 m	Al Faw WPD 50 m	Basrah Air-Port WPD 50 m	Umm Qasr WPD 50 m
Winter	87.5397591	42.21069322	55.99137204	87.62433381	130.5381834	152.4202756
Spring	86.41636349	56.882973	69.38885722	86.49985286	159.1442269	181.5428621
Summer	106.7403533	113.0547567	117.643539	118.8434782	311.4828692	307.7103902
Autumn	72.67523734	39.28513849	47.24909565	72.74545101	126.2638157	132.3460438

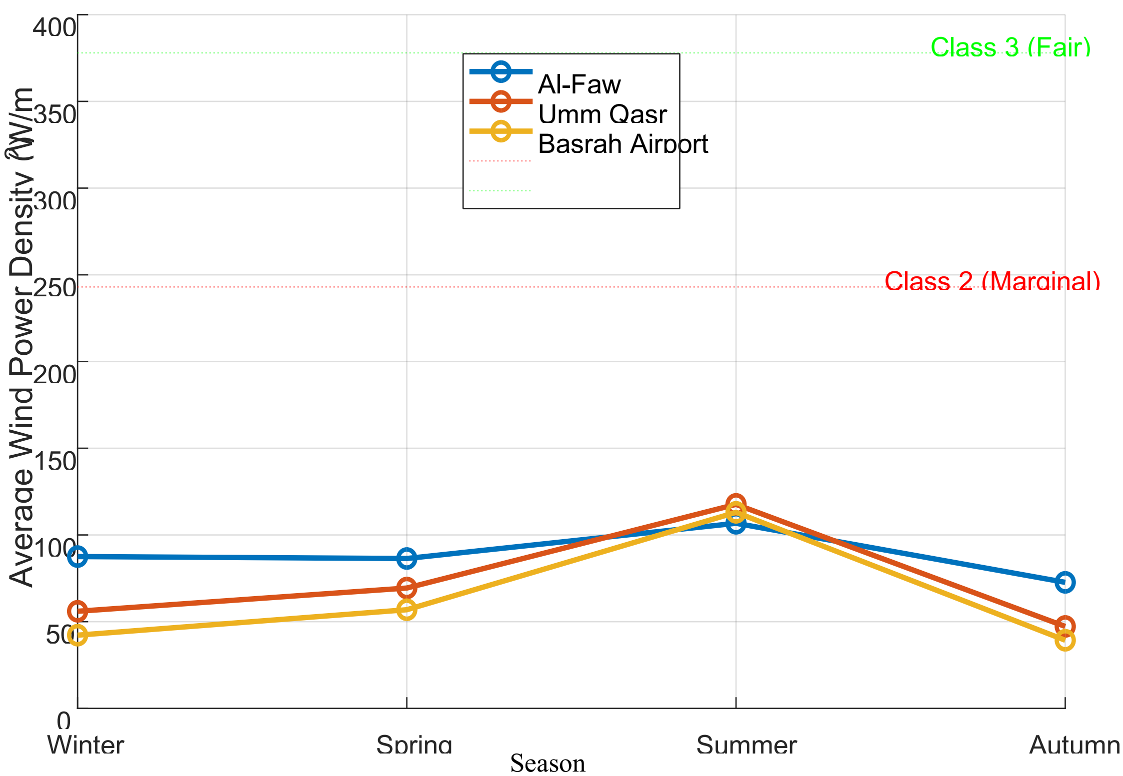

Fig 6: Seasonal mean wind power density (W/m²) at 10 m height by season and site (Al-Faw Grand Port, Umm Qasr, Basrah Airport) for the study period 2020–2022.

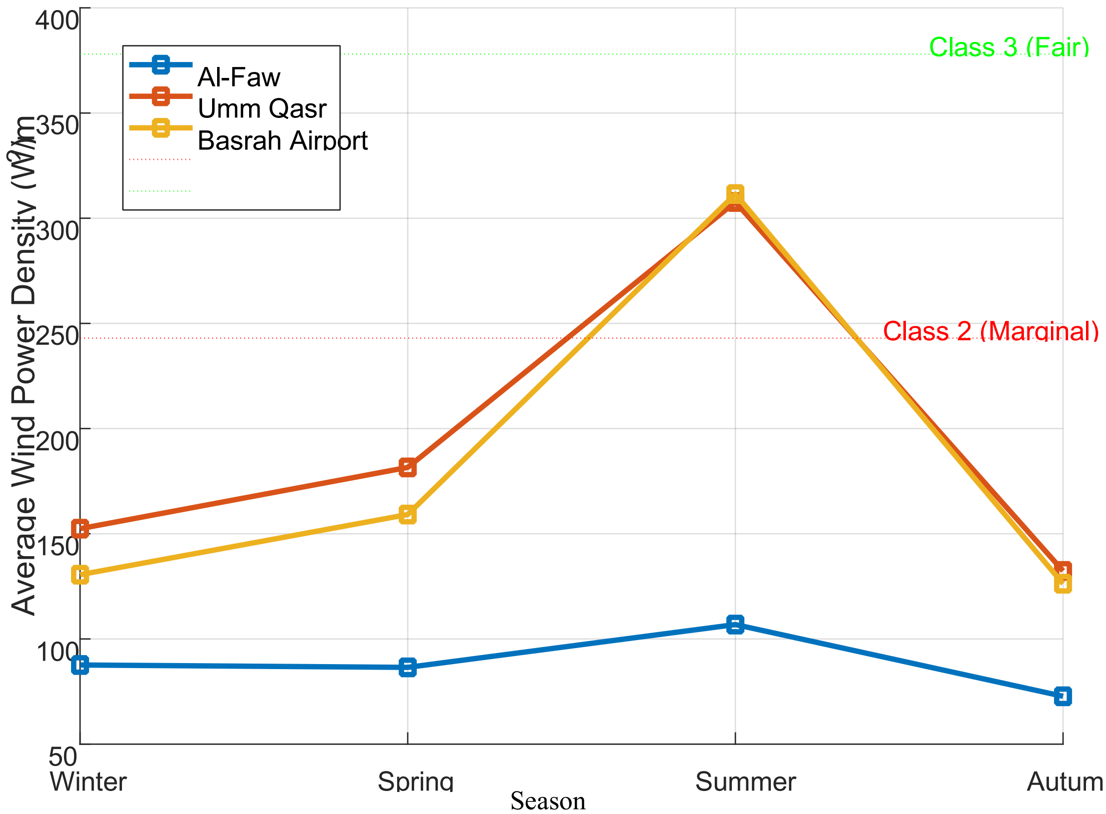

Fig 7: Seasonal mean wind power density (W/m²) at 50 m height by season and site (Al-Faw Grand Port, Umm Qasr, Basrah Airport) for the study period 2020–2022.

Winter months demonstrated moderate to high WPD values during years with active winter Shamal conditions. January mean WPD at Al-Faw ranged from 35.5 W/m² (2021) to 170.7 W/m² (2020), while December values varied from 19.9 W/m² (2022) to 467.7 W/m² (2020). February exhibited the greatest interannual range, with WPD values spanning from 14.5 W/m² (2020) to 307.8 W/m² (2021), reflecting the episodic nature of winter Shamal events.

Spring and autumn months generally produced lower WPD values, with April and October frequently recording the annual minima. At Basrah Airport, April mean WPD values at 10 m height were consistently low across all years: 52.2 W/m² (2020), 4.1 W/m² (2021), and 15.2 W/m² (2022). Similarly, October displayed reduced wind power availability, with values of 22.4 W/m² (2020), 114.0 W/m² (2021), and 36.9 W/m² (2022) at the same location.

3.1.3. Spatial Gradient Analysis:

A methodical analysis of wind power density (WPD) at the three study sites shows that the density of wind power is a steady coastal to inland gradient, i.e., the closer the area is to the Arabian Gulf, the greater the wind power density of that area (Figure 8). Annual average WPD at 10m below the sea level decreased between Al-Faw (coastal) and Umm Al-Qasr (intermediate, about 50km inland) and then to Basrah Airport (inland, about 100km inland). A clear coastal-inland gradient is observed: WPD at 10 m decreases from 139.3 W/m² (Al-Faw, coastal) to 78.3 W/m² (Umm Qasr, ~5 km inland) to 55.6 W/m² (Basrah Airport, ~100 km inland). However, with only three sites, linear trends are not statistically justified.

The spatial gradient at 50 m height was slightly weakened but remained substantial. Mean annual WPD values of 236.9 W/m² (Al-Faw), 192.8 W/m² (Umm Qasr), and 160.6 W/m² (Basrah Airport) specified a 32% reduction from coast to inland. The reduced gradient magnitude at higher elevations proposes that marine boundary layer effects effecting coastal wind speeds reduce with increasing height above the surface.

The spatial gradient demonstrated temporal variability, with the coastal advantage most marked during strong Shamal wind events and reduced during calm periods. During November 2020, when intense northwesterly winds prevailed, Al-Faw recorded WPD values 2.2 times greater than Basrah Airport at 10 m height. On the contrary, during April 2021, a outstandingly calm month, the spatial differences were minimal, with Al-Faw exhibiting only 1.6 times the WPD of Basrah Airport.

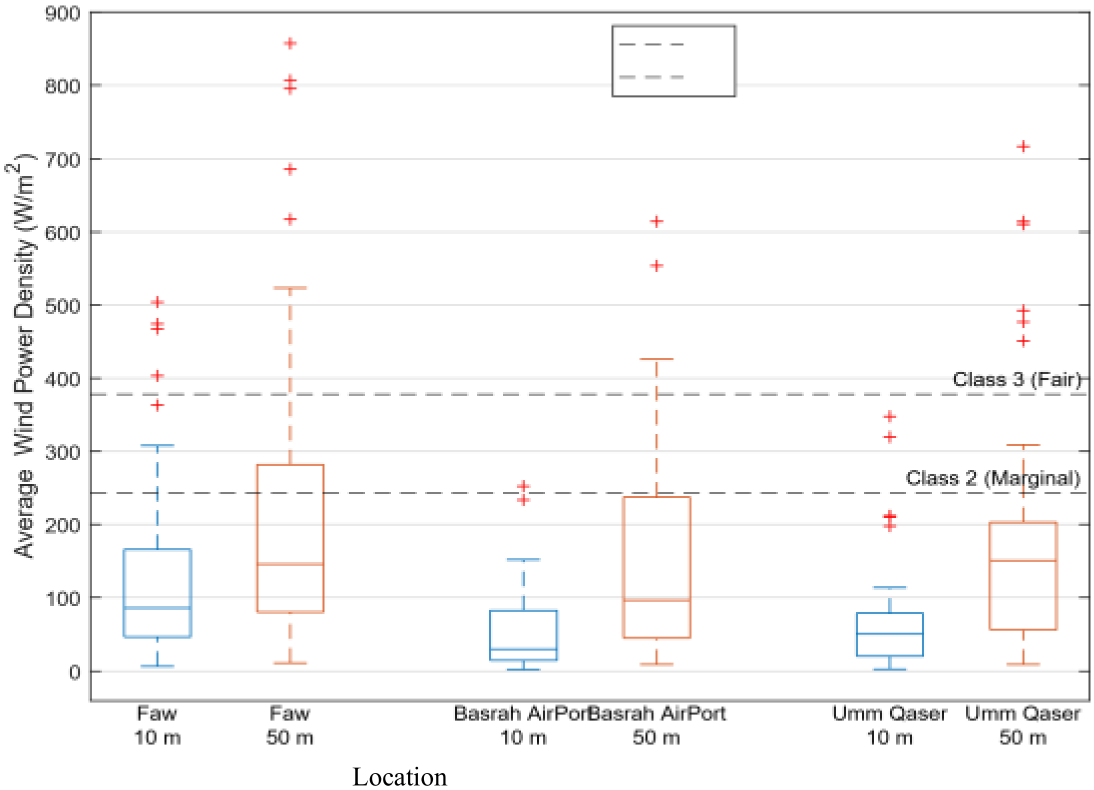

Fig 8: Wind Power Density Distribution by Site and Height (Monthly Means) Outliers represent rare extreme events (e.g., November 2020 Shamal wind).

Monthly grouped box plots revealed the distribution characteristics of WPD at each location. Al-Faw displayed the widest distribution range and highest median values, with occasional extreme outliers exceeding 400 W/m² at 10 m height during intense wind events. Basrah Airport showed the narrowest distribution with lowest median values, reflecting its inland position and greater surface roughness effects. Umm Qasr exhibited intermediate characteristics, with distribution parameters falling consistently between the coastal and inland extremes.

The spatial gradient in WPD was maintained throughout most months, with Al-Faw consistently exhibiting higher values than Umm Qasr and Basrah Airport. However, the magnitude of this gradient varied temporally. During strong Shamal events, the coastal advantage of Al-Faw was most pronounced, with WPD values 3-5 times greater than inland locations ststed in figure 9. During calm periods, the spatial differences diminished, though Al-Faw retained a modest advantage due to reduced surface roughness effects near the coastline.

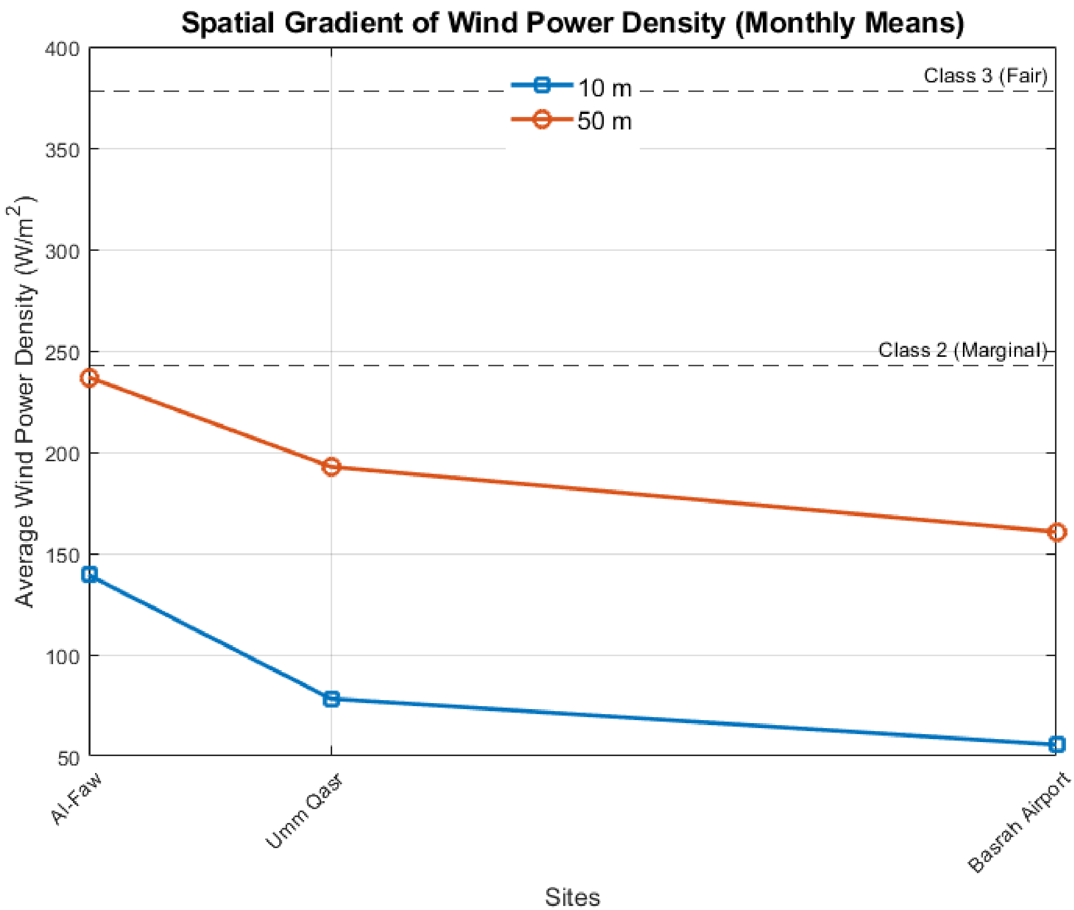

Fig 9: Spatial gradient of wind power density (monthly means)

3.1.4. NREL Wind Power Classification:

Using the NREL wind power classification to annual average values of WPD offered objective evaluation of wind power capacity at every site under study and height (Table 3). All three sites were in Class 1 (0–243 W/m²), at 10 m above the ground, which is a poor wind resource that cannot sustain commercial development of wind energy. Al-Faw even with the largest 10 m WPD (139.3 W/m²), was still highly below the 243 W/m² to reach Class 2 marginal viability. Even lower values of basrah Airport (55.6 W/m²) and Umm Qasr (78.3 W/m²) were observed which are lower in Class 1.

While summer monthly WPD exceeds 243 W/m² (e.g., 307 W/m² in June), the annual mean remains below Class 2. Thus, the site is classified as NREL Class 1 (Not Suitable) for utility-scale projects. Seasonal peak potential does not override annual viability as shown in figure 10.

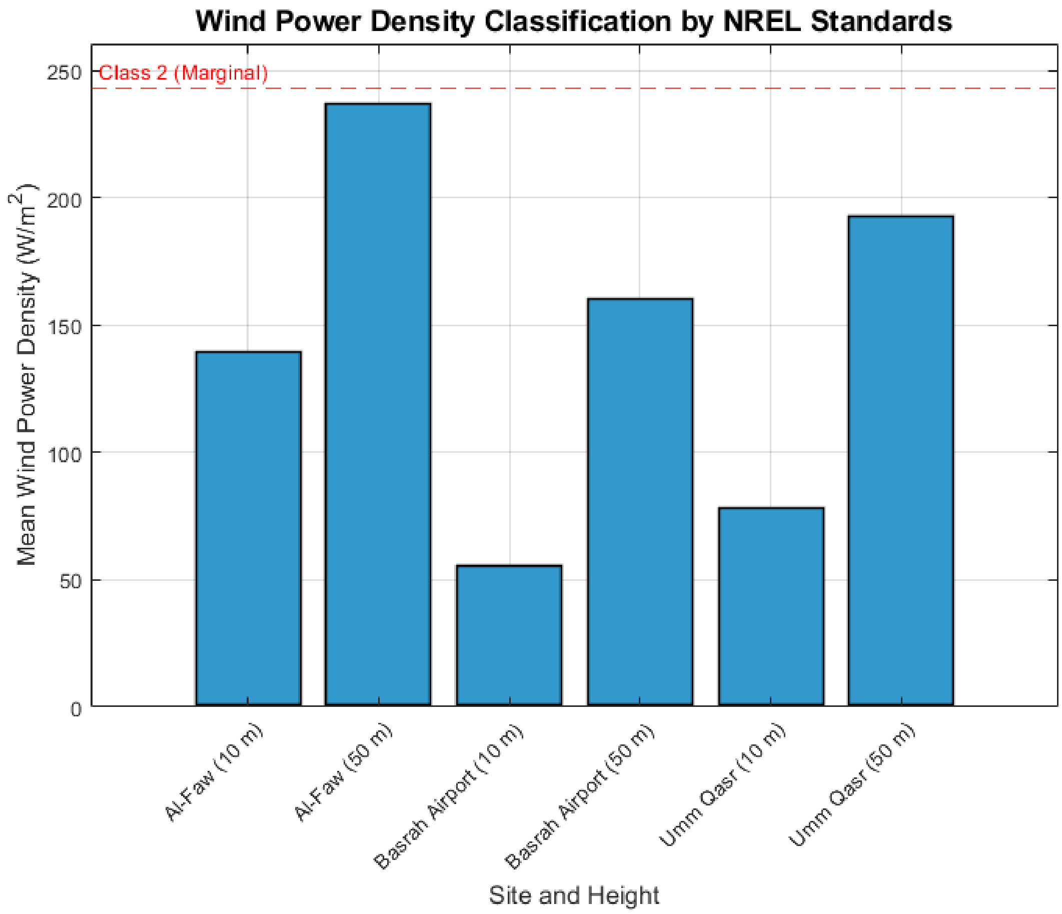

Fig 10: Wind power density classification by NREL Standards.

Basrah Airport was still at Class 1 and WPD was 160.6 W/m², which clearly shows that the place is not permissive to develop wind power even in high turbine setups. The 50 m WPD is merely 66% of the lowest Class 2 limit indicating that tremendous height gain or major technological progress would be necessary to get to the inland site economically viable.

Umm Qasr was in a borderline position with 50 m WPD of 192.8 W/m², which is determined as Class 1 bordering Class 2. This mid-coastal site has potential of marginal wind energy applications, especially at high wind summer periods when instantaneous WPD is often Class 2, and sometimes Class 3. The possibility of seasonal or hybrid wind-solar facilities at Umm Qasr may be considered due to the maximum wind speed in the summer, which is the period when the solar radiation is at its maximum in the area.

Analysis of monthly values of WPD versus the NREL level of classification indicated that all three locations sometimes achieve Class 2 or above when the wind is good. Al-Faw at the height of 50 m safely increased the Class 2 (243 W/m²) when there were 12 out of 36 months where observations were made and it increased to Class 3 (378 W/m²) r more in 4 months when the particularly strong Shamal events took place. Only 3 months can be attributed to extreme winter Shamal events, which put Basrah Airport in Class 2 territory. Umm Qasr attained Class 2 in 6 months' time and was mainly in summer and occasional high-wind incidents in the winter season.

The time variability of classification status suggests that although, on average, annual conditions are not economically viable to commercial viability standards, the wind resource has enough variability to generate economically viable power production over large parts of the year. Such temporal pattern implies that wind energy facilities in the Southern part of Iraq may best serve as part of hybrid renewable energy facilities or as seasonal ancillary power generators as opposed to baseload generation power facilities. which indicated that Al-Faw has Class 1 classification at a 10 m height and 147.7 W/m² of annual average WPD. At a more appropriate heights of a modern wind turbine hub, 50 m, the classifications enhanced slightly but were still largely undesirable. Al-Faw attained Class 2 with the mean WPD of 236.9 W/m², close to the 243 W/m² Class 2 threshold. This marginal classification implies that the development of the wind energy at Al-Faw may be viable under good economic conditions especially when the turbine is located above the hub height of more than 50 m or when hybrid renewable energy systems are applied.

The observation in the previous study that the area can possibly be more productive at greater elevation is confirmed by the current analysis as that there is a slight enhancement to Class 2 at 50 m height, however, still lower than the Class 3 level which is usually regarded as the best site to develop wind farms.

4. CONCLUSIONS

This comprehensive three-year assessment of wind power density across southern Iraq's coastal zone and the findings show that wind resource in the area is still marginal as per the global standards but bears some features that may facilitate strategic use of renewable energy in the area when conditions are favorable.

None of the three stations is currently suitable for standalone commercial utility-scale wind energy generation. Based on annual mean WPD: Al-Faw (236.9 W/m² at 50 m) approaches but does not meet the Class 2 threshold (243 W/m²); Umm Qasr (192.8 W/m² at 50 m) and Basrah Airport (160.6 W/m² at 50 m) are clearly Class 1. However, during peak summer months (June–August), Al-Faw and Umm Qasr at 50 m regularly exceed Class 2 thresholds, and Al-Faw exceeds Class 3 during strong Shamal events, suggesting potential for seasonal supplemental or hybrid wind-solar applications, contingent on dedicated techno-economic analysis.

The analysis shows that there is a distinct coastal-inland gradient as wind power density declines by 60% from coastal Al-Faw (139.3 W/m² at 10 m) to inland Basrah Airport (55.6 W/m²) over a 100 km transect. Extrapolation of height to 50 m yields significant improvement (1.7–2.9× factors), with Al-Faw is close to NREL Class 2 marginal viability at 236.9 W/m². Nevertheless, none of the sites is above the Class 3 level that is usually discussed as the best one to build a commercial wind farm.

Seasonal variations indicate highest wind power densities (>300 W/m² at 50 m at coastal sites), occur during summer which is the same time as Iraq experiences its peak electricity demand due to air conditioning loads. This is a strategic edge in wind energy integration because of this time fit. Nevertheless, the fact that the standard deviation is high (greater than the mean values) means that the intermittency is high and typical of episodic Shamal wind regimes, which creates issues with grid integration and demand energy storage or a reserve capacity.

Marginal wind resources imply that wind farms will not be economical on their own but hybrid systems consisting of wind and solar photovoltaics have a good potential to solve this problem because of the complementary seasonal and diurnal generation patterns. The significant improvement in WPD with the increase in distance 10 m to 50 m, suggests that the modern turbines with hub heights of 80 to 100 m may have improved classifications especially at the coast. Since the spike of wind resources throughout the summer season suggests the presence of seasonal storage systems or a combination with hybrid renewable arrangements.

The present study is the first multi-height and multi-site comparative evaluation of the wind power density in the coastal area in Iraq, which provides the necessary baseline information to support evidence-based planning in the area of renewable energy. Although the wind resources in southern Iraq are below the optimum rates in the global scales, some strategic options such as hybrid, height optimization, and seasonal energy planning would allow the country to make significant contributions to the renewable energy portfolio and energy security goals of Iraq.

Author Contributions: A.1, A.2 and A.3; **methodology,** A.2; **software,** A.1; **validation,** A.3; **formal analysis,** A.1 and A.2; **investigation,** A.2; **resources,** A.3; **data curation,** A.1; **writing-original draft preparation,** A.2; **writing—review and editing,** A.1 and A.3; **visualization,** A.1; **supervision,** A.3; **project administration,** A.2. All authors have read and agreed to the published version of the manuscript

Funding: This research received no external funding

Institutional Review Board Statement: Not applicable

Informed Consent Statement: Not applicable.

Acknowledgments: The authors express their sincere gratitude to Mustansiriyah University, College of Science, Department of Atmospheric Science.

Conflicts of Interest: authors declare no conflicts of interest.

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