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Propagation characteristics of underwater noise from operational offshore wind farms and assessment of potential auditory interference risk to fish

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Introduction: With the rapid expansion of offshore wind power, the potential impact of underwater noise from operational wind farms on marine organisms has attracted increasing concern.

Methods: To investigate the acoustic characteristics of underwater noise from wind farms, this study measured underwater noise data from an operational wind farm in the Nanpeng Island area of Yangjiang, Guangdong, and analyzed its time-frequency and spectral characteristics.

Results: The results indicate that the acoustic energy in the study area was primarily concentrated at low frequencies below 1000 Hz. Distinct wind turbine noise characteristics were observable at both 2 m and 5 m water depths, and noise levels exhibited a decreasing trend with increasing distance from the wind farm. The wind turbine noise exhibited discrete spectral features, with peak center frequencies mainly distributed at 31.5 Hz, 63 Hz, 160 Hz, and 630 Hz. Outside the wind farm, only the 31.5 Hz and 63 Hz peak bands were prominent. However, within the farm, owing to the proximity of a greater number of operating turbines, all peak frequency bands were more pronounced, and an additional peak emerged around the 250 Hz band. Furthermore, by comparing the underwater noise spectra with fish auditory sensitivity curves, a preliminary assessment was conducted to determine the species-specific spatial extent of potential noise perception: the auditory threshold of the large yellow croaker was exceeded only within the wind farm at frequencies around 380 Hz; the threshold for the green grouper was exceeded at a distance of 500 m from the wind farm; the threshold for the pearl gentian grouper was exceeded at 5.5 km; and the Japanese seabass, having the lowest auditory threshold, had its threshold exceeded at all monitoring stations.

Discussion: The findings of this study provide a data reference for assessing the acoustic environmental impact of offshore wind farms and for planning integrated "wind-fishery" development.

KEYWORDS
offshore wind farm, operational phase, wind turbine noise, fish auditory threshold, ecological risk assessment, wind-fishery co-location

1 Introduction

Offshore wind power has emerged as a key option for energy transition due to its multiple advantages, including higher wind speeds, greater power generation efficiency, no land occupation, and proximity to electricity load centers (Zhong et al., 2010). By the end of 2025, the global cumulative grid-connected installed capacity of offshore wind power had reached 89.2 GW, and it is projected to reach 227 GW by the end of 2030 (RenewableUK, 2026). Located at a strategic point in the South China Sea, Yangjiang possesses the second largest sea area in Guangdong Province and adjoins the Greater Bay Area electricity consumption center, offering favorable conditions for offshore wind development (Huang and Zhang, 2024). In line with the strategic development needs of China's offshore wind sector under the "dual carbon" goals, Yangjiang has become a core demonstration area for the national offshore wind industry, leveraging its superior marine wind energy resources and policy support. As of May 2025, Yangjiang had established a planned total installed capacity of 20,000 MW for offshore wind, with a grid-connected capacity exceeding 6,000 MW, accounting for 50% of the provincial total and ranking second nationally (Yangjiang Municipal Development and Reform Bureau, 2025). The development history of Yangjiang's cumulative installed offshore wind capacity is illustrated in Figure 1. However, despite these advantages, the potential impact of continuous operational noise from the increasing number of offshore wind turbines worldwide on the underwater soundscape has attracted growing concern.

During the operation of offshore wind farms, there are three primary pathways through which turbines radiate noise into the underwater environment (Nedwell and Howell, 2004): The first is the transmission of airborne noise into the water; the second, and the dominant source of underwater noise during operation, is the direct propagation of noise generated by pile foundation vibrations into the water column; the third involves noise transmission from the pile foundation into the seabed, which is then re-radiated into the water. A study by Yoon et al. (2023) indicates that the acoustic characteristics of underwater noise from operational wind farms are closely related to wind speed, rotor speed, and tower vibration. Wang (2014), during underwater noise measurements of operational offshore wind turbines, found multiple dominant tonal components at a distance of 15 m from a turbine, with the highest noise intensity reaching approximately 100 dB re 1 μPa. Underwater noise monitoring of operational turbines by Zhang et al. (2016) revealed that acoustic energy was primarily concentrated in the low-frequency bands and exhibited relatively low levels. Research by Niu et al. (2016) indicated that the underwater noise spectra generated by operating turbines of different power ratings and foundation structures are generally consistent, characterized by a distinct decrease in overall sound intensity with increasing frequency. Existing studies have demonstrated that the acoustic energy from operational offshore wind turbines is mainly concentrated in the low-frequency range below 1000 Hz (Lucke et al., 2007). Within this frequency band, multiple signal peaks are present, and the noise exhibits pronounced discrete spectral characteristics, primarily generated by mechanical vibrations from the gearbox and generator within the wind turbine (Yang et al., 2024); these features represent the signature of operational turbine noise (Liu et al., 2019a). The peak frequencies vary among turbines in different wind farms and are largely correlated with turbine power ratings (Berg, 2004).

Existing studies have shown that the continuous noise generated during the operational phase of wind farms has a certain impact on the underwater acoustic environment and will persist over decades of operation (Su, 2020; Zhu et al., 2026). The intensity of this noise gradually increases with wind speed and turbine size (Madsen et al., 2006; Andrea et al., 2021). From the overall background of the marine soundscape, the underwater low-frequency sound field is primarily dominated by two types of core noise sources: one is natural environmental noise generated by wind, waves, currents, etc., and the other is anthropogenic noise generated by shipping, underwater engineering, etc (Cui et al.,

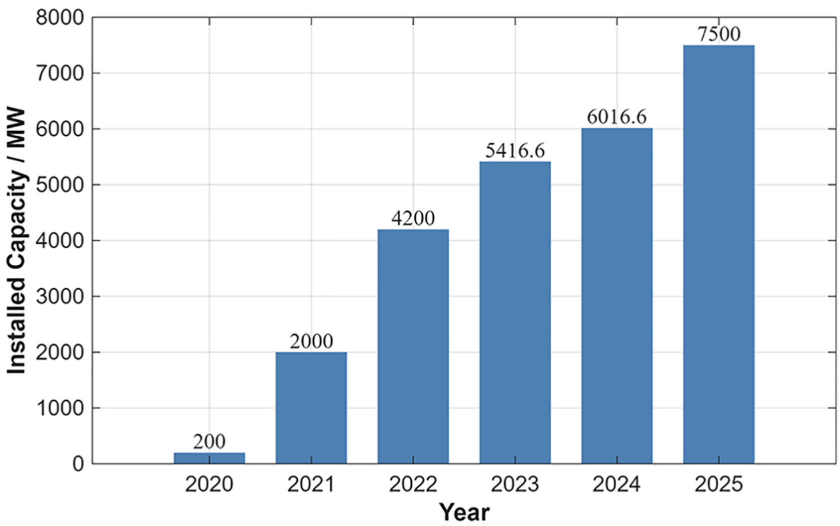

FIGURE 1
Development history of the cumulative installed capacity of the Yangjiang offshore wind farm (values for 2025 are estimates). (Data sourced from the official statistical reports of the Yangjiang Municipal Development and Reform Bureau).

2023). Unlike intermittent, highly dynamic shipping noise and randomly fluctuating natural noise, operational wind farm noise is characterized by long duration, concentrated low-frequency energy, and pronounced discrete spectral features. It will contribute a long-term, stable sound pressure level to the existing marine soundscape, thereby potentially altering the acoustic habitat of marine organisms.

Existing research has shown that the auditory sensitivity of aquatic sensitive organisms, such as fish, is primarily concentrated in the low-frequency range (Ladich and Fay, 2013). Experimental data on closely related species within the Sciaenidae family by Ramcharitar et al. (2006) indicate that their peak auditory sensitivity typically occurs at 200–700 Hz. Underwater noise from offshore wind farms may exert various effects on fish exposed to it, but these effects are species-specific and context-dependent. Kim et al. (2025) assessed the species-specific physiological responses of marine fish to operational noise from offshore wind farms through controlled experiments and emphasized the necessity of considering underwater noise in marine ecosystem management. Siddagangaiah et al. (2024), through long-term *in-situ* monitoring, found that increased noise levels in wind farm areas may alter the vocalization behavior of fish. Wahlberg and Westerberg (2005) indicated that fish with different auditory capabilities could detect turbine noise within a range of 0.4–25 km, with the detection distance depending on factors such as turbine size and number, fish auditory capability, and background noise level. Zhang et al. (2021) found that the frequency bands of turbine noise overlapped with the vocalization frequencies of the marbled rockfish, potentially inducing masking effects. Experimental research by Wang et al. (2023) demonstrated that exposure to 200 Hz noise at 110 dB re 1 μPa induced temporary threshold shifts (TTS) and behavioral changes in black rockfish, although these responses were recoverable. These studies indicate that current assessments of operational wind farm noise on fish primarily focus on impacts within the audible zone, masking zone, and behavioral/physiological response zone; however, the delineation of these zones requires targeted analysis based on the background noise characteristics of the sea area and the auditory traits of the target species. Moreover, “wind-fishery co-location” is becoming an important model for the synergistic development of offshore wind power and marine ranching. Liu et al. (2023), using passive acoustic techniques for continuous day-and-night monitoring of large-scale caged fish populations, found that the vocalization signals of fish are predominantly in the low- to mid-frequency range. This spectral overlap suggests that wind farm noise may pose potential interference with the acoustic behavior of cage-cultured fish, thereby affecting marine aquaculture benefits and the sustainable utilization of fishery resources.

This study took the Yangjiang offshore wind farm as the research object. Through field observations of underwater noise from the operational wind farm in Yangjiang, the propagation characteristics of underwater noise signals with distance in this area were revealed, and a preliminary assessment was conducted of the potential auditory interference risk of wind turbine noise to adjacent fish. The findings of this study provide a data reference for assessing the acoustic environmental impact of offshore wind farms and for planning the “wind-fishery co-location” model.

2 Materials and methods

2.1 Study area

The study area is located in the Nanpeng Island sea area, Yangjiang City, Guangdong Province. The water depth in this area ranges from 21 to 32 m, with an annual average wind speed of no less than 5.5 m/s. The nearest distance from the studied wind farm area to the coastline is approximately 19.5 km. The locations of the 128 turbines, each with a unit capacity of 5.5 MW, installed within this sea area are shown in Figure 2. In this study, the pile foundation indicated by “×” in the figure serves as the reference turbine location, and all distances from the wind farm mentioned in the text are measured from this reference pile.

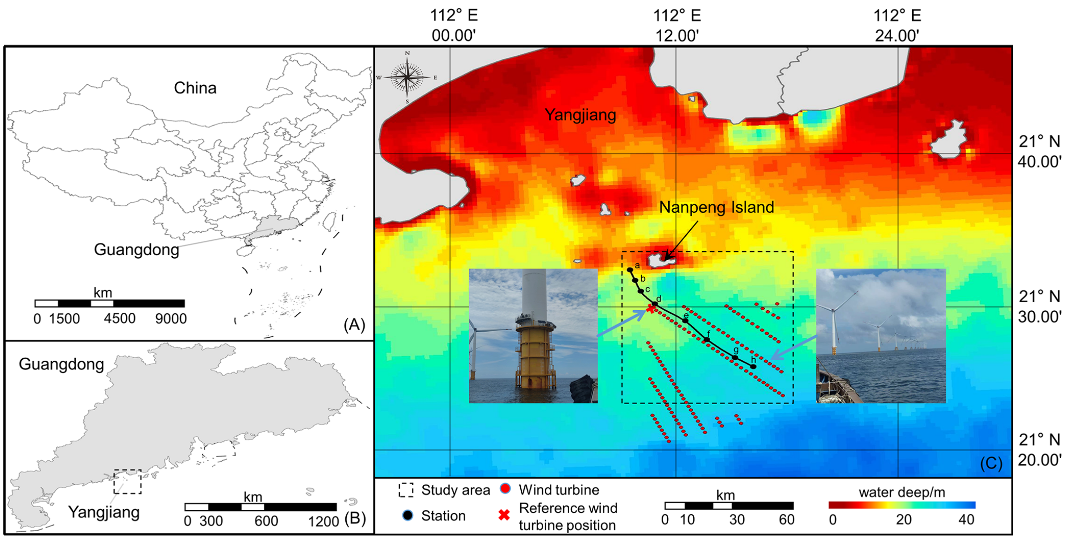

FIGURE 2
Schematic map of the study area: **(A)** map of China; **(B)** regional map of Guangdong Province; **(C)** detailed map of the study area.

2.2 Data measurement

On August 9, 2024, the research team recorded underwater noise data in the Nanpeng Island wind farm area off Yangjiang. On the day of measurement, the water temperature in the study area was approximately 28.8 °C, the average wind speed was about 6.1 m/s, the wind direction was southerly, and overall sea conditions were relatively calm. Underwater noise data were recorded using an XReceiver Pro self-contained hydrophone, independently developed by Shanghai Jiao Tong University. This hydrophone has a sensitivity of -195 dB re 1V/μPa and a frequency bandwidth of 20 Hz to 50 kHz, with a minimum equivalent self-noise of less than 30 dB re 1V/μPa at 1 kHz and less than 20 dB re 1V/μPa at 10 kHz, effectively meeting the low-frequency noise measurement requirements of this study. The instrument had been sent to a certified professional underwater acoustic metrology laboratory for calibration before delivery. During data acquisition, the preamplifier gain was set to 46 dB, and the sampling frequency was set to 96 kHz. Upon arrival at each predetermined station, the vessel's engine and other potential sound-emitting sources were shut down, allowing the vessel to drift freely with the current. Once the hull motion stabilized, the self-contained hydrophone was activated and deployed to the target water depth to commence data measurement. During deployment, a weight was attached to the instrument and the cable was secured to keep it in a relatively vertical posture in the water, thereby minimizing flow noise or cable motion interference during measurement. Considering the relative concentration of acoustic energy in the near-surface layer of shallow waters, the hydrophone was deployed at two depths—2 m and 5 m—at each station to elucidate the horizontal propagation characteristics of underwater noise from the operational wind farm. The measurement duration at each station was no less than 10 min. Specific deployment times and station information are provided in Table 1. Stations a through d were located outside the wind farm area, arranged from far to near relative to the farm; stations e through h were situated inside the wind farm area. The specific observation route is illustrated in Figure 2.

2.3 Data processing

During this experiment, underwater noise data from the operational wind farm were recorded at eight stations in Yangjiang. To analyze the propagation characteristics of the underwater noise from the operational wind farm, the measured noise data were processed as follows: First, data preprocessing was conducted. Based on the vessel passage times recorded on site and through screening of the time-frequency spectrograms of the noise signals, data segments corresponding to periods of vessel passage and abnormal data segments caused by irregular hydrophone motion were removed, in order to minimize interference from identifiable shipping noise and flow noise. Next, the preprocessed data were segmented into sections of 1 s duration. The power spectral density of the underwater noise signals was calculated using Welch's method, employing a Hanning window weighting function with a window overlap of 75%. By averaging the power spectral density of every 10 s of data and constructing a time-frequency matrix, the time-frequency characteristics of each station were obtained. The specific processing steps are as follows:

The voltage signal U (unit: V) recorded by the hydrophone was converted into the sound pressure signal P (unit: μPa) using the following formula:

$$P = U \cdot \frac{V_{ADC}}{10^{(G_{PreAmp}+S_{Sens})/20}} \tag{1}$$

In Equation 1, V_{ADC} is the ADC voltage range of the hydrophone (V_{ADC}= 4.096 V); G_{PreAmp} is the preamplifier gain of the hydrophone (G_{PreAmp}= 46 dB); and S_{Sens} is the hydrophone sensitivity (S_{Sens}= -195 dB re 1V/μPa).

The converted continuous sound pressure signal was segmented into I intervals, each with a duration of 1 s. The signal of the i-th segment is expressed as:

$$P_i[n] = P((i-1) \cdot N_s + n \cdot T_s) \tag{2}$$

In Equation 2, n = 0, 1, … N_s-1, $N_s$is the number of sampling points per segment; $T_s$is the sampling interval ($T_s = 1/f_s$, with $f_s$being the sampling frequency); and i = 1,2,…I, where I represents the duration of data measured at each station (in seconds).

Welch's method was applied to the segmented sound pressure signal sequences to calculate the power spectral density $PSD(f_k)$:

$$PSD(f_k) = \frac{2}{f_s \cdot \sum_{n=0}^{N-1} w^2[n]} \left| \sum_{n=0}^{N-1} w[n] \cdot P_i[n] \cdot e^{-j2\pi kn/N} \right|^2 \tag{3}$$

In Equation 3, $w[n]$ is the Hanning window function, with n = 0, 1, … N-1, N is the number of Fourier transform points, and k is the frequency index (k = 0, 1, … N/2).

The average power spectral density $\overline{PSD_t}$ (unit: dB) was calculated for every 10 s of data:

$$\overline{PSD_t} = 10 \cdot \log_{10}\left(\frac{1}{M} \cdot \sum_{m=1}^{M} PSD_m(f_k) \right) \tag{4}$$

In Equation 4, m = 1, 2, … M, with M being the duration of each 10 s data segment (M = 10); t = 1, 2, … j, where j is equal to the number of average power spectral density values calculated for each station ($j = I/10$).

The calculated average power spectral densities of each station were used to construct a time-frequency matrix $TF(t, f_k)$, yielding the time-frequency characteristics of each station:

TABLE 1 Data measurement records.

Observation station	Start time	End time	Station latitude and longitude
a (5.5 km)	8:42	8:54	21°32'32"N;112°09'22"E
b (3.5 km)	9:08	9:20	21°31'50"N;112°09'37"E
c (2 km)	9:29	9:40	21°31'08"N;112°09'52"E
d (500 m)	9:49	9:59	21°30'17"N;112°10'35"E
e (inside)	10:42	10:52	21°29'08"N;112°12'08"E
f (inside)	11:08	11:18	21°27'52"N;112°13'13"E
g (inside)	11:34	11:45	21°26'40"N;112°14'39"E
h (inside)	12:09	12:20	21°26'02"N;112°15'35"E

$$TF(t, f_k) = \left[\overline{PSD_1} \overline{PSD_2} \cdots \overline{PSDj} \right] \quad (5)$$

In Equation 5, t represents the time axis and $f_k$represents the frequency axis.

3 Results

Previous studies have demonstrated that the acoustic energy of underwater noise generated during wind farm operation is primarily concentrated in the low-frequency range (within 1000 Hz) (Lou and Ma, 2024). Furthermore, sound propagation in shallow seas exhibits a cutoff frequency, where only a few low-order modes can propagate when the sound wave frequency falls below a certain threshold. Considering the spectral characteristics of operational wind farm noise, the auditory sensitive frequency bands of the target fish species, and the potential presence of harmonic components, the frequency range for analysis in this study was selected as 20 Hz to 2000 Hz.

3.1 Time-frequency characteristics of underwater noise from operating wind farms

(1) Time-frequency characteristics of underwater noise outside the wind farm.

Time-frequency characteristics analysis was conducted on the operational underwater noise data from four stations arranged from far to near around the wind farm. The resulting time-frequency plots for each station at different water depths are presented in Figure 3. In each time-frequency plot, the horizontal axis represents the duration of data measurement, labeled by station; the vertical axis represents frequency; and the color intensity reflects the sound pressure level. The results indicate that at both 2 m (Figure 3A) and 5 m (Figure 3B) water depths, the noise signals with higher energy were primarily concentrated within the 20-1000 Hz frequency band. As the distance from the measurement stations to the wind farm decreased from 5.5 km to 500 m, the underwater noise intensity exhibited an increasing trend. At Station a, located 5.5 km from the wind farm, the noise radiated from the farm underwent substantial attenuation over long-distance propagation due to geometric spreading and water absorption; consequently, only signals with the most favorable propagation conditions were detectable, resulting in the lowest noise intensity. As the distance decreased to Station b (3.5 km) and Station c (2 km), propagation losses diminished, and noise intensity increased accordingly. When the measurement point approached Station d (500 m), located at the periphery of the wind farm, signals from a greater number of noise sources within the farm could effectively arrive, forming a stronger sound pressure distribution. Notably, distinct discrete spectral features were observable at this station (indicated by the red dashed box in Figure 3).

(2) Time-frequency characteristics of underwater noise within the wind farm.

Time-frequency characteristics analysis was performed on the operational underwater noise data from four stations located inside the wind farm area. The results revealed that at both 2 m (Figure 4A) and 5 m (Figure 4B) water depths, the noise signals with higher energy were also primarily concentrated within the 20-1000 Hz frequency band. As shown in Figure 4, when positioned inside the wind farm, the measurement points were exposed to an increased number of effective noise sources within the farm. Acoustic waves from multiple sources may accumulate energy underwater, leading to an elevation in the overall sound pressure level. Additionally, the propagation distances between internal measurement points and the noise sources were shorter, resulting in weaker energy attenuation due to geometric spreading and water absorption, thereby further increasing noise intensity. By comparing the time-frequency plots at different water depths, it was observed that all four stations within the wind farm exhibited pronounced discrete spectral features at both depths (indicated by the red dashed boxes in Figure 4), suggesting enhanced underwater noise intensity within these frequency bands at both measured depths. A comparison of time-frequency plots across stations revealed that the discrete spectral components at Stations e and f exhibited higher sound pressure levels and broader frequency coverage than those at Stations g and h. This pattern may be attributed to their closer proximity to a greater number of operating turbines. During field measurements, it was observed that not all turbines were operational; specifically, the visible turbines in the vicinity of Stations e and f were all running normally, whereas some turbines within the visible range near Stations g and h were not in operation. This operational discrepancy is likely a primary factor contributing to the differences in acoustic field characteristics observed at various locations within the wind farm.

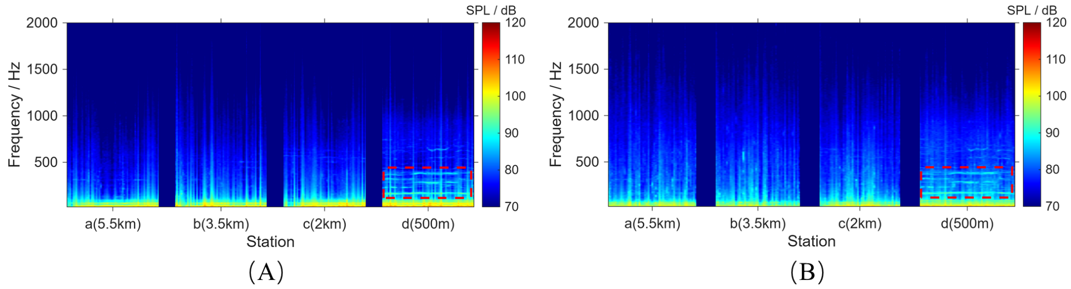

FIGURE 3
Time-frequency plots of underwater noise measured at various distances outside the wind farm area at water depths of **(A)** 2 m and **(B)** 5 m.

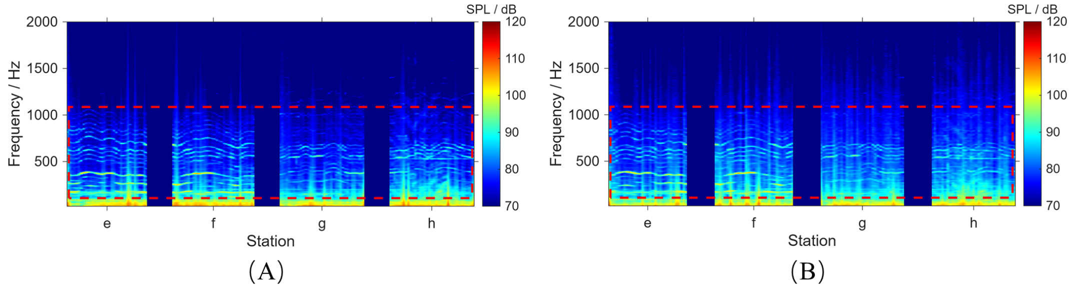

FIGURE 4
Time-frequency plots of underwater noise within the wind farm area at water depths of **(A)** 2 m and **(B)** 5 m.

In summary, through the time-frequency characteristics analysis of operational underwater noise from the wind farm at different depths and distances, the propagation characteristics of noise intensity gradually attenuating from the interior to the exterior of the wind farm were revealed. Furthermore, the wind turbine noise exhibited discrete spectral features, with acoustic energy primarily concentrated in the low-frequency range below 1000 Hz, reflecting the dominant low-frequency characteristics of underwater noise from operational wind farms. Comparative analysis showed that distinct wind turbine noise was observable at both 2 m and 5 m water depths, with similar time-frequency characteristics, indicating good consistency of wind turbine noise features within the upper water column.

3.2 Frequency-domain characteristics of underwater noise from operational wind farms

As indicated by the time-frequency characteristics analysis, the energy of operational wind turbine noise was primarily concentrated in the low-frequency range, exhibiting similar noise characteristics at both 2 m and 5 m water depths. To further clarify the spectral composition of the noise and the propagation characteristics of noise intensity at varying distances, this section presents a frequency-domain characteristics analysis of noise signals both inside and outside the wind farm area, taking the 2 m water depth as an example.

(1) Frequency-domain characteristics of underwater noise outside the wind farm.

A 1/3-octave band analysis was conducted on the noise signals from the four stations measured from far to near outside the wind farm area (Figure 5), clearly revealing the spectral distribution and propagation characteristics of the wind turbine noise. The results indicate that within the 20-2000 Hz frequency band, the noise spectrum levels at all stations exhibited an overall decreasing trend with increasing frequency. This pattern not only aligns with the general characteristics of marine ambient noise but also reflects the inherent "low-frequency energy dominance" property of operational wind farm noise. As the distance from the measurement

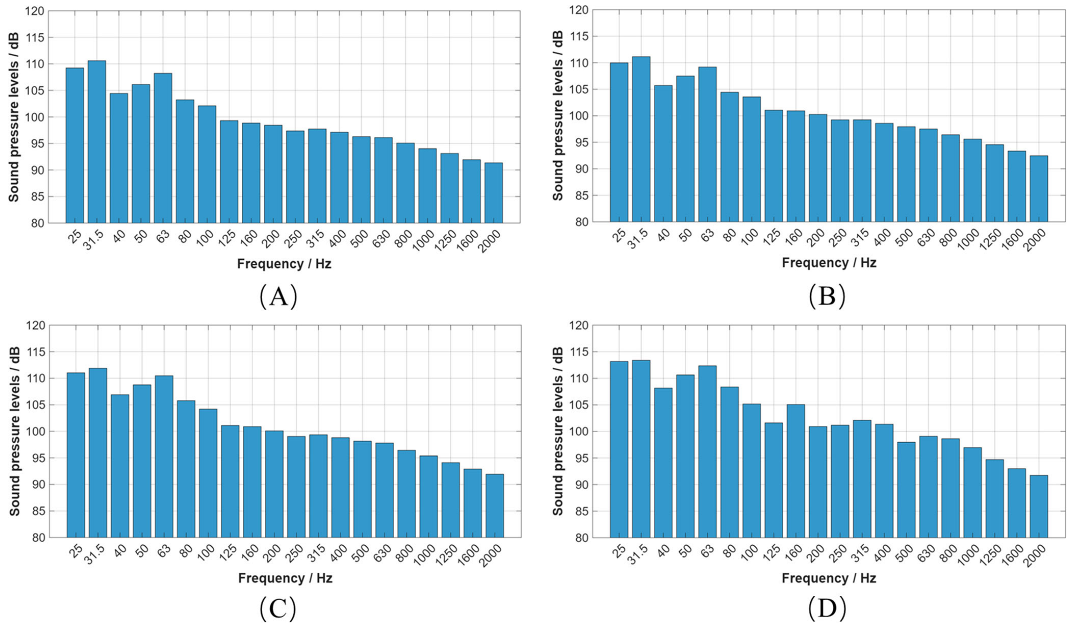

FIGURE 5
1/3-octave band spectra at a water depth of 2 m at various distances outside the wind farm area: **(A)** station a; **(B)** station b; **(C)** station c; **(D)** station d.

stations to the wind farm decreased (from Station a to Station d), the sound pressure levels across various frequency bands increased accordingly. At the nearest measurement point, Station d (500 m), several discrete spectral peaks emerged in the spectrum, corresponding to the characteristic radiated noise of operating wind turbine units. From the spectrum at Station d, it can be clearly observed that the peak center frequencies of wind turbine noise were primarily concentrated in five frequency bands: 31.5 Hz, 63 Hz, 160 Hz, 315 Hz, and 630 Hz. Among these, the 31.5 Hz and 63 Hz bands constituted the core peak frequencies, with their energy primarily originating from the characteristic frequencies of wind turbine tower structural vibrations, gearbox, or generator mechanical vibrations. Due to the low absorption coefficient and slow propagation attenuation of low-frequency acoustic waves in water, these two bands exhibited relatively high sound pressure levels across all four stations. In contrast, the peaks in the 160 Hz, 315 Hz, and 630 Hz bands were mainly attributed to higher-order harmonics generated by mechanical vibrations of the turbines or noise from localized components. Their energy was relatively weaker and only prominent at the near-field Station d; with increasing distance, these peaks gradually attenuated and were submerged within the ambient noise.

(2) Frequency-domain characteristics of underwater noise within the wind farm.

A 1/3-octave band analysis was conducted on the noise signals from the four stations within the wind farm area (Figure 6). The results indicate that, compared with stations outside the wind farm area, the sound pressure levels at all stations inside the area were elevated. In terms of spectral characteristics, the peak center frequencies of wind turbine noise within the area were primarily concentrated in five frequency bands: 31.5 Hz, 63 Hz, 160 Hz, 400 Hz, and 630 Hz. Compared with the off-site stations, the peak observed within the wind farm at 400 Hz corresponded to the 315 Hz peak outside the farm. This shift is hypothesized to result from the cumulative effects and band coverage effects of multi-turbine noise within the farm: under 1/3-octave band analysis, the 315 Hz and 400 Hz bands share an overlapping region, and the accumulation of multi-source noise may cause energy redistribution between adjacent bands, leading to the formation of a more pronounced peak in the 400 Hz band. Further comparison of the spectra across stations within the farm revealed that Stations e and f exhibited higher spectral levels in the 160 Hz and 400 Hz bands, along with the emergence of an additional peak in the 250 Hz band. This pattern may be attributed to their closer proximity to a greater number of operating turbines. In contrast, the spectral peaks at Stations g and h were more constrained, with slightly lower overall sound pressure levels. Combined with the field observation that some turbines in this area were not operational, this suggests that the spatial distribution and operational status of noise sources directly influence the spectral morphology and overall sound pressure levels of the internal acoustic field.

From the frequency-domain characteristics analysis presented above, it can be observed that the peak center frequencies common to wind turbine noise both inside and outside the wind farm area were 31.5 Hz, 63 Hz, 160 Hz, and 630 Hz, reflecting the inherent radiation characteristics of mechanical and structural vibrations of wind turbine units. To more intuitively analyze the propagation characteristics of underwater noise intensity from the operational wind farm, the peak center frequencies from all eight stations were integrated and analyzed, yielding Figure 7, which illustrates the variation of wind turbine noise peak center frequencies from outside to inside the wind farm at different water depths. In the figure, the data points represent the sound pressure levels at the corresponding peak center frequencies for each station, while the fitted curves highlight the trend of sound pressure level variation at these peak center frequencies across stations. The results indicate

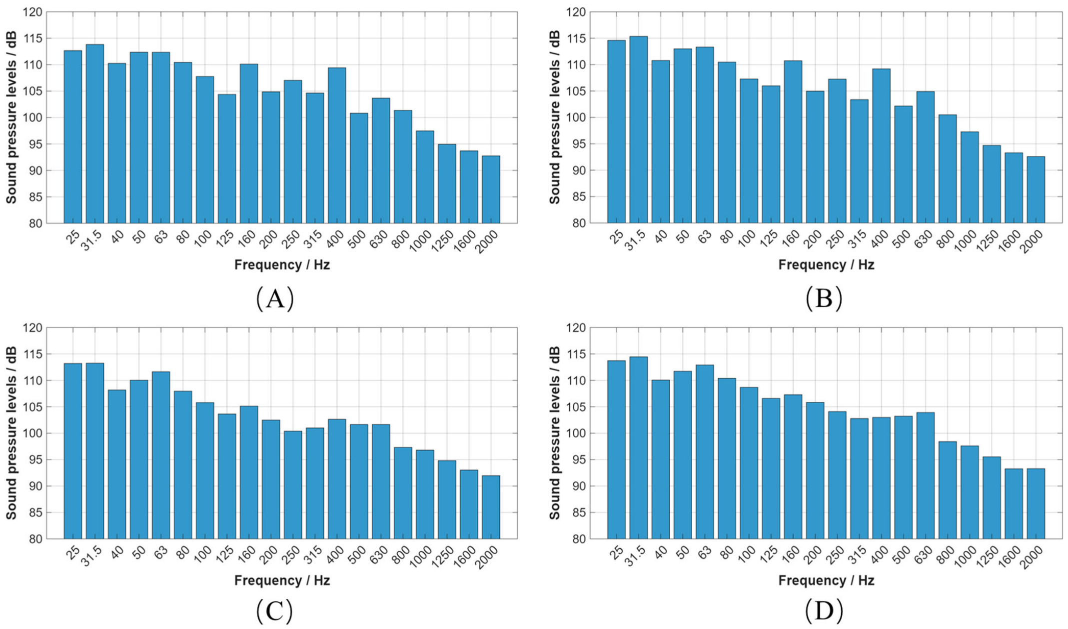

FIGURE 6
1/3-octave band spectra at a water depth of 2 m within the wind farm area: **(A)** station e; **(B)** station f; **(C)** station g; **(D)** station h.

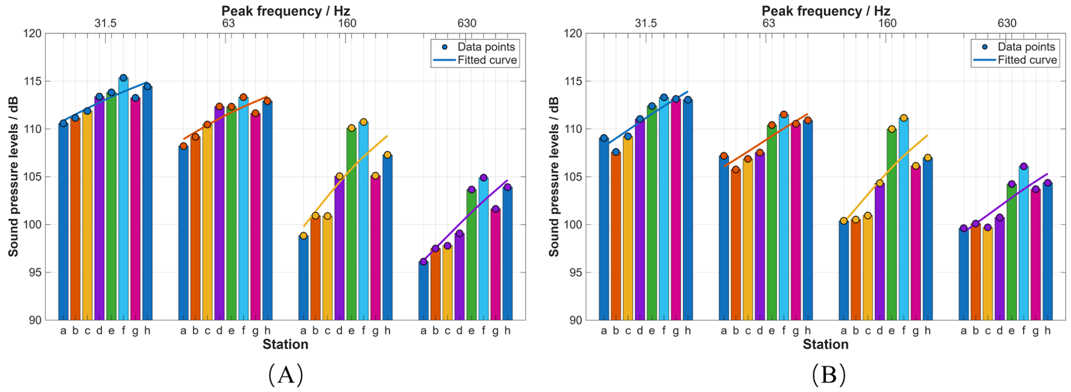

FIGURE 7
Variation in the peak center frequencies of wind turbine noise from outside to inside the wind farm at water depths of **(A)** 2 m and **(B)** 5 m.

that from outside (Stations a-d) to inside (Stations e-h) the wind farm, the fitted curves at each peak center frequency exhibited a gradually increasing trend, and the sound pressure levels at each station showed an overall decreasing trend with increasing peak center frequency. To intuitively present the spatial variation trend of wind farm underwater noise with distance, linear regression analysis was performed between the sound pressure levels at each peak center frequency and station location (a–h, from outside to inside the wind farm), and the results are shown in Table 2. The fitting results indicate that the coefficients of determination R^2 at each peak center frequency ranged from 0.58 to 0.83, and the fitted curves can reasonably characterize the spatial trend of increasing sound pressure levels with decreasing distance. A comparative analysis revealed that this trend exhibited good consistency at both 2 m and 5 m water depths. It should be noted that this regression analysis was based on spatially sequential sampling data along a single transect; all measurement points belong to the same continuous sound field of the wind farm rather than representing independent replicate samples, thus entailing the issue of spatial pseudoreplication. Therefore, this analysis serves only as a descriptive illustration of the spatial trend, and the derived significance statistic p is provided for reference only and should not be used for independent statistical hypothesis testing.

Based on the comprehensive analysis presented above, it can be concluded that underwater noise from operational wind farms exhibits low-frequency dominant characteristics, with its acoustic energy primarily concentrated in the frequency range below 1000 Hz. As the distance from the measurement points to the wind farm increases, the sound pressure levels at each peak center frequency show a gradually attenuating trend, with high-frequency components attenuating more rapidly due to propagation losses, while low-frequency components possess stronger retention capability in the far field. Furthermore, within the wind farm area, owing to the proximity of a greater number of operating turbines, the discrete components in the spectrum are more pronounced, and the overall sound pressure levels are higher than those outside the area. These patterns exhibit good consistency at both 2 m and 5 m water depths.

TABLE 2 **Linear regression fitting results of sound pressure levels at each peak center frequency versus stations from outside to inside at different water depths.**

Depth (m)	Indicator	Peak center frequency (Hz)			
		31.5	63	160	630
2	p	0.0065	0.0073	0.0285	0.0045
	R^2	0.735	0.725	0.578	0.764
5	p	0.0017	0.0044	0.0287	0.0082
	R^2	0.828	0.766	0.577	0.715

3.3 Assessment of potential auditory interference risk of operational wind farm noise to fish

To assess the potential auditory interference risk of operational wind farm noise to commercially important fish species in the surrounding waters, this study selected four fish species active in the Yangjiang sea area—the large yellow croaker (*Larimichthys crocea*), green grouper (*Epinephelus awoara*), pearl gentian grouper (*Epinephelus fuscoguttatus* ♀ × *Epinephelus lanceolatus* ♂), and Japanese seabass (*Lateolabrax japonicus*)—as the focal subjects. Based on the auditory sensitivity curves of these four fish species measured using the electrophysiological auditory brainstem response (ABR) method by Yin (2017); Zhu (2020); Liu et al. (2019b), and Chen et al. (1981), an integrated analysis was conducted by comparing these curves with the average power spectral density curves of operational wind farm underwater noise obtained in this study, yielding the comparative results presented in Figure 8. As can be observed from the figure, the peak frequencies of operational wind farm underwater noise overlap with the auditory sensitive frequency ranges of the aforementioned fish species, suggesting that wind turbine operational noise may be detectable by these fish and could potentially impact their auditory function. The detailed analysis results are as follows:

Among the four fish species, the large yellow croaker exhibited a relatively higher auditory threshold. At distances beyond 500 m from the wind farm, the maximum peak intensities of wind farm noise at both 2 m and 5 m water depths were below its auditory threshold (Figures 8A, B). However, within the wind farm, the noise intensity at approximately 380 Hz exceeded the auditory threshold

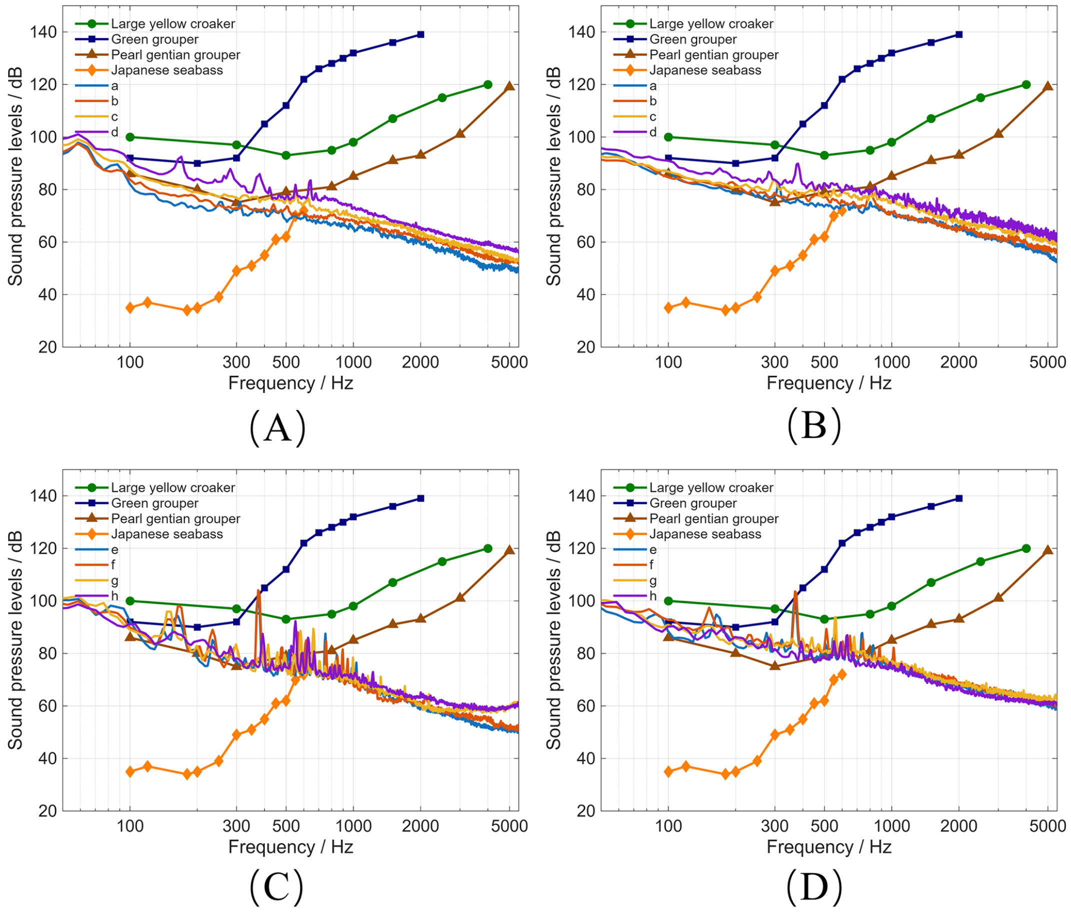

FIGURE 8
Comparison of average power spectral density curves of operational wind farm underwater noise with fish auditory sensitivity curves: **(A)** 2 m (outside the wind farm); **(B)** 5 m (outside the wind farm); **(C)** 2 m (inside the wind farm); **(D)** 5 m (inside the wind farm).

of the large yellow croaker, while the peak intensities at other frequencies remained below the threshold (Figures 8C, D). These results indicate that beyond 500 m from the wind farm, the intensity of wind farm noise does not reach the auditory threshold of the large yellow croaker; within the farm, it may be detectable only within specific frequency bands.

The auditory threshold of the green grouper was slightly lower than that of the large yellow croaker. At a distance of 500 m from the wind farm and at 2 m water depth, the wind farm noise intensity at approximately 169 Hz exceeded the auditory threshold of the green grouper (Figure 8A). Within the wind farm area, the peak noise intensities at both approximately 169 Hz and 380 Hz exceeded its auditory threshold (Figures 8C, D). This suggests that the green grouper may perceive wind farm noise at a distance of 500 m, with potentially greater perception within the wind farm.

The pearl gentian grouper exhibited a relatively low auditory threshold. At a distance of 5.5 km from the wind farm area, the underwater noise intensity already exceeded its auditory threshold. The Japanese seabass had the lowest auditory threshold among the four species, with noise intensities at all eight stations, both inside and outside the wind farm, exceeding its threshold. These findings indicate that the pearl gentian grouper and Japanese seabass are more sensitive to underwater noise and may have a relatively larger perceptual range for wind farm noise.

This study conducted a preliminary assessment of the potential auditory interference risk for different fish species by comparing wind farm noise spectra with fish auditory thresholds. As the fish auditory thresholds used in this study were all physiological minimum detection limits measured by the ABR method in the laboratory, which differ from perceptual thresholds in the natural soundscape, this spectral comparison serves only as a preliminary screening method for the potential detectability of noise by fish. The results indicate that the peak frequencies of underwater noise generated during wind farm operation overlap with the auditory sensitive frequency bands of the fish, with the extent to which auditory thresholds were exceeded varying among species. The large yellow croaker exhibited a relatively high auditory threshold, which was exceeded only within the wind farm at the 380 Hz frequency band. The auditory threshold of the green grouper was exceeded at a distance of 500 m from the wind farm, with potentially greater perception inside the farm. The pearl gentian grouper had a relatively low auditory threshold, which was exceeded at 5.5 km. The Japanese seabass possessed the lowest auditory threshold, which was exceeded at all stations, suggesting a potentially larger perceptual range for wind farm noise. These findings indicate that underwater noise from the wind farm may be detectable by the target fish species at varying distances, and that noise intensities in certain frequency bands exceeded fish auditory thresholds by several to tens of decibels, potentially exerting effects on their auditory function.

4 Discussion

4.1 Discussion of wind farm noise acoustic characteristics

This study aimed to investigate the propagation characteristics of underwater operational noise from an offshore wind farm as a function of distance, as part of a preliminary survey to assess its potential impact on the marine ecosystem. Based on extensive experimental and observational data, Tougaard et al. (2020) proposed a linear model to evaluate the general correlation between estimated total sound pressure level and factors such as distance, wind speed, and turbine size. The model indicates that distance to the turbine is the most significant factor explaining measured sound pressure levels, with wind speed and turbine size having a lesser influence. Accordingly, this study focused on the effect of distance.

This study identified stable discrete tonal peaks in the noise spectrum at frequencies such as 31.5 Hz, 63 Hz, 160 Hz, and 630 Hz. Previous research through field measurements has demonstrated that operational noise from wind farms is primarily generated by mechanical vibrations. These vibrations are transmitted into the water through the tower and foundation, forming the tonal (line spectrum) characteristics of the underwater noise (Yang et al., 2018, Yang et al., 2024). Marmo et al. (2013) using numerical simulations and experimental data analysis, indicated that mechanical vibrations often exhibit tonal features. Low-frequency signals from gear meshing typically occur below 50 Hz, while noise from electromagnetic interactions is distributed in the low to mid-frequency range of 50 Hz to 2 kHz. Their study identified primary noise peaks, including 31.5 Hz, 80 Hz, 125 Hz, and higher-frequency harmonics such as 560 Hz and 600 Hz, suggesting that these discrete peaks are directly related to drive train design parameters (e.g., number of gear stages, generator pole pairs). By integrating the mechanistic analyses and spectral feature comparisons from existing studies, the stable discrete peaks measured in this study show consistency with previously reported mechanical noise model predictions and *in-situ* vibration measurements of operational wind turbines. It can therefore be reasonably inferred that these discrete spectral peaks primarily originate from underwater radiated noise generated by mechanical vibrations during wind turbine operation.

Furthermore, compared with the findings of Huo et al. (2024) for the Yangjiang wind farm—which observed that discrete spectral features essentially disappeared beyond a distance of 4 km—the effective propagation distance of underwater wind farm noise in the present study was somewhat extended. This discrepancy is hypothesized to result primarily from the difference in the scale of turbine installations between the study areas: the area investigated by Huo et al. contained 55 turbines, whereas the wind farm in this study comprises a significantly larger number. A wind farm constitutes an aggregation of multiple independent noise sources (turbines). In the far field, the total sound field is dominated by the energy summation of sound pressure from individual sources. A greater number of simultaneously operating turbines may enable signals that would have attenuated below the ambient noise level in the context of a smaller-scale wind farm to remain detectable within a larger-scale installation. Tougaard et al. (2020) developed a simple model for the aggregated noise around multi-turbine wind farms, demonstrating that the cumulative noise level several kilometers from a wind farm can be elevated, with the measured level at such distances exceeding that from any single turbine. The phenomenon observed in this study suggests that as the scale of a wind farm increases, the acoustic impact range may also expand. However, the specific pattern of this expansion and the extent of the impact require further investigation.

4.2 Discussion on the effects of wind farm noise on fish

This study selected four commercially important fish species inhabiting the waters around the Yangjiang sea area to evaluate the potential auditory interference risk of operational wind farm noise on them. Among these, the large yellow croaker has developed into one of China's eight dominant export aquaculture species and is also the largest-scale marine farmed fish in the country (Zhong et al., 2014). Groupers are a key species in marine cage aquaculture in southern China; in Xiamen City alone, the number of marine cages for farming groupers has exceeded 30,000 per year (Qin et al., 2004). Consequently, assessing the potential auditory interference risk of operational wind farm noise on these target fish species holds significant economic and ecological value.

This study conducted a preliminary assessment of the potential auditory interference risk of the wind farm to adjacent commercially important fish species by comparing operational wind farm noise spectra with fish auditory thresholds. In terms of ecological relevance, the measurement depths in this study covered the relevant water layers where the target fish species may potentially inhabit or forage. Ichthyological data indicate that the large yellow croaker is a bentho-pelagic fish species with a broad distribution range, and its active water layers encompass the mid to upper layers. The Japanese seabass can be active at depths reaching 5 m. Although groupers primarily inhabit depths of 10-50 m, their diet includes crustaceans and small fish; the vertical distribution of these prey organisms may drive groupers into the upper water column to feed (Marcinkevicius, 2024). Furthermore, research by Cui et al. (2023) indicates that at frequencies below 400 Hz, the noise power spectral density does not vary significantly with depth, and the reduction in mean power spectrum level is less than 5 dB. Therefore, although measurements in the upper water layer cannot be directly equated to absolute sound pressure levels at the bottom, they can reflect the comparative trend relative to fish auditory thresholds and provide a certain reference significance for the preliminary assessment of the potential acoustic impact of wind farm noise on the target fish species.

This assessment focused primarily on the audible sound pressure range for fish, employing a common preliminary screening method used internationally to evaluate the potential auditory impact of noise on aquatic life. In this study, only the sound pressure component of the underwater noise was measured, and the particle motion component of the sound field was not synchronously measured. Assessments based solely on sound pressure data would significantly underestimate the actual audible range of noise and the potential auditory interference risk for species sensitive to particle motion. Therefore, the audible distances provided by this assessment are conservative results based solely on sound pressure thresholds, and the actual perceptual range and potential impacts may be greater. In this regard, our data analysis paid particular attention to sound pressure levels in the low-frequency bands most closely associated with particle motion. The sound pressure characteristics in this frequency band can, to some extent, indirectly reflect the potential influence of the particle motion component (Schulz-Mirbach et al., 2020), but cannot fully substitute for direct particle motion measurements. Therefore, this assessment represents only a preliminary conservative judgment based on sound pressure data. It aims to identify the potential perceptual range where wind turbine noise sound pressure levels exceed species-specific auditory thresholds, providing a reference for identifying priority areas for subsequent research. Future studies should incorporate both hydrophones and particle motion sensors for *in-situ* measurements to more comprehensively and accurately assess the potential acoustic impacts of noise on fish with different auditory types.

Field observations revealed the presence of fish schools and sea turtles within the Yangjiang wind farm area (Figure 9). This phenomenon suggests that organisms insensitive to operational wind farm underwater noise may be able to conduct normal activities within the wind farm area. Furthermore, the presence of wind turbine foundations may weaken hydrodynamic forces; the relatively calm water flow on the lee side of the piles, in particular, provides an ideal refuge area for fish within the farm. Research by Bennun et al. (2021) indicates that with appropriate siting, the impacts of wind farms on marine organisms can be minimized, and they may even yield positive effects on biodiversity. Wilhelmsson et al. (2006) found that the growth of blue mussels on wind turbines increased the abundance of fish and benthic fauna in the wind farm area. Lindeboom et al. (2011) reported that the establishment of wind turbine farms provided important resting areas and refuges for fish and marine mammals, with the number of species in the area increasing by 37. Although somewhat incidental, the findings from this field investigation hint at the possibility of coexistence between operational wind farms and marine fish species with low sensitivity or high tolerance to wind farm noise. Future research should integrate long-term monitoring for a comprehensive assessment.

This study represents the first attempt to integrate field-measured data from a large-scale offshore wind farm in the Yangjiang sea area with auditory thresholds of multiple fish species. Through systematic field observations, the propagation characteristics of operational wind farm noise—specifically the gradual attenuation of noise intensity with increasing distance from the wind farm—were revealed. Furthermore, by comparing the noise spectra with the auditory sensitivity curves of four locally economically important fish species, a preliminary assessment was conducted to determine the species-specific spatial extent of potential noise perception, providing baseline acoustic exposure data to inform preliminary planning for "wind-fishery co-location" models. However, this study has several limitations: (1) The data were derived from single-day observations conducted in summer, with limited temporal coverage. The conclusions of this study represent only the noise characteristics and risk levels under the operating conditions corresponding to the observation period, and cannot fully capture the dynamic variations across all seasons and operating conditions of the wind farm. Their long-term generalizability requires further verification through subsequent continuous monitoring data across multiple seasons and sea states. Particularly under high wind conditions (e.g., during typhoons or strong seasonal winds), turbines may enter a fully-loaded operational state, potentially leading to increased noise levels and enhanced low-frequency components, which could expand the perceptual range for fish. (2) This study primarily focused on the horizontal propagation characteristics of underwater noise from the operational wind farm. The measurements only covered the upper water layer, and the vertical variation of the sound field (especially near the seabed) remains unclear. Limited by the vertical coverage of the observation water layers, this study was unable to fully characterize the vertical variation of noise throughout the entire water column in

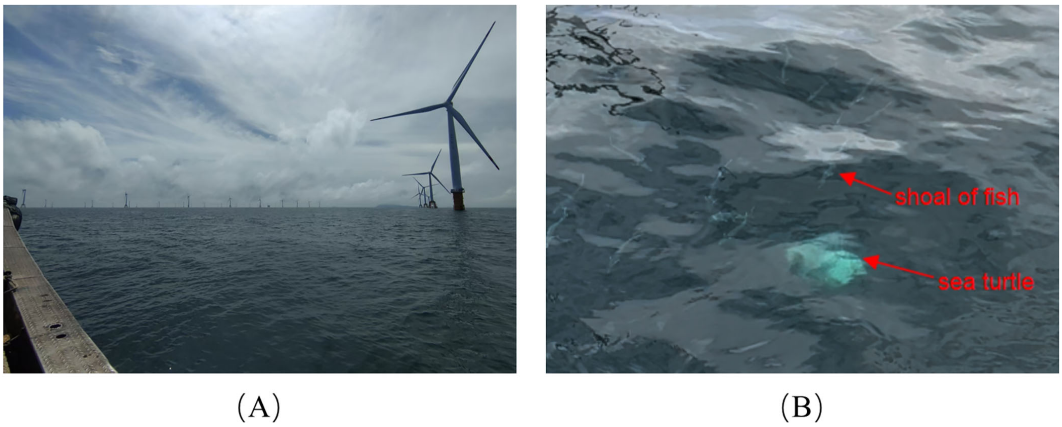

FIGURE 9
Biological activity within the wind farm area: **(A)** overview; **(B)** detailed view.

the study area, which may result in certain deviations in characterizing the actual noise exposure levels for fish species that prefer demersal or benthic habitats. The relevant conclusions need to be further validated with long-term monitoring data across the full water column.

5 Conclusions

This study conducted field observations in the Nanpeng Island sea area off Yangjiang, recording underwater noise data from an operational offshore wind farm at multiple stations. Through signal processing and analysis of the noise data, and by comparing the results with fish auditory sensitivity curves, the following conclusions were drawn:

1. The acoustic energy of underwater noise generated during wind farm operation was primarily concentrated in the frequency range below 1000 Hz, exhibiting an overall trend of decreasing sound pressure level with increasing frequency. The wind turbine noise displayed typical low-frequency narrowband and discrete spectral characteristics, with multiple prominent peaks within the low-frequency range.
2. Underwater noise generated during wind farm operation exhibited propagation characteristics of gradually attenuating noise intensity from the interior to the exterior of the wind farm at both 2 m and 5 m water depths, demonstrating good consistency of wind turbine noise features within the upper water column. With increasing distance up to 5.5 km, only signals with the most favorable propagation conditions remained detectable.
3. The peak frequencies of underwater noise generated during wind farm operation overlapped with the auditory sensitive frequency bands of the fish, with the extent to which auditory thresholds were exceeded varying among species. The large yellow croaker exhibited a relatively high auditory threshold, which was exceeded only within the wind farm at the 380 Hz frequency band. The auditory threshold of the green grouper was exceeded at a distance of 500 m from the wind farm. The pearl gentian grouper had a relatively low auditory threshold, which was exceeded at 5.5 km. The Japanese seabass possessed the lowest auditory threshold, which was exceeded at all stations. These findings indicate that underwater noise from the wind farm may be detectable by the aforementioned fish species at varying distances.

In summary, through the analysis of underwater noise at multiple stations, this study revealed the propagation characteristics with distance of underwater noise from the operational offshore wind farm in Yangjiang and conducted a preliminary assessment of the potential auditory interference risk of wind farm noise to adjacent fish. Future research should incorporate long-term, multi-dimensional monitoring to establish a more comprehensive ecological impact assessment framework for wind farms, thereby providing scientific support for the sustainable development of wind farms and the establishment of "wind-fishery co-location" models.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

CL: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Visualization, Writing – original draft. PZ: Conceptualization, Data curation, Funding acquisition, Methodology, Project administration, Software, Validation, Writing – review & editing. JT: Funding acquisition, Investigation, Writing – review & editing. HW: Investigation, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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