

Article

Short-Term Passive Acoustic Monitoring Indicates Associations Between Fish Vocal Activity and Offshore Wind Farm Noise

Qitong Ge ^{1,†} , Shouguo Yang ^{2,†} , Hongyi Guo ³ , Xuguang Zhang ^{1,*}  and Xianming Tang ^{2,*} 

¹ Engineering Technology Research Center of Marine Ranching, College of Oceanography and Ecological Science, Shanghai Ocean University, Shanghai 201306, China; ge_qitong@163.com

² Hainan Provincial Key Laboratory of Tropical Maricultural Technology, Hainan Academy of Ocean and Fisheries Sciences, Haikou 571126, China; yangshouguo82@163.com

³ Shanghai Universities Key Laboratory of Marine Animal Taxonomy and Evolution, Shanghai Ocean University, Shanghai 201306, China; hy-guo@shou.edu.cn

* Correspondence: zhang_xuguang@163.com (X.Z.); hn.tangxm@aliyun.com (X.T.)

† These authors contributed equally to this work.

Abstract

The rapid expansion of offshore wind farms (OWFs) is reshaping coastal soundscapes through operational turbine noise, while the acoustic responses of soniferous fishes within operational wind-farm areas remain difficult to assess using conventional fishery surveys. In this study, passive acoustic monitoring (PAM) was deployed within the Yangjiang Offshore Wind Farm to examine short-term associations among underwater sound fields, turbine spatial layout, a turbine startup event, and putative fish-call activity. Fish-call detections were lower along the transect with 550 m turbine spacing than along the 1300 m transect, coinciding with higher measured sound pressure levels in the 550 m spacing layout. Acoustic activity in the central zone of the 1300 m array was 6.46 times higher than that of the 550 m layout, suggesting that lower-noise areas within wind farms may provide favorable acoustic conditions for detectable fish-calling activity. During a turbine startup event, fish-call detection rates temporarily decreased during the transient increase in sound pressure level and subsequently recovered as the underwater noise returned toward baseline conditions. These patterns indicate that PAM can capture short-term soundscape-associated variation in fish-calling activity or call detectability. We further propose a conceptual trade-off framework in which foundation-associated habitat benefits and operational noise may jointly shape the acoustic space use of soniferous fishes in OWFs.

Keywords: passive acoustic monitoring (PAM); offshore wind farm; underwater noise; Sciaenidae; fish vocal activity



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Key Contribution: A method is presented for detecting subtle changes in the vocalization activity of fish within the operational area of an offshore wind farm using short-term passive acoustic monitoring. A conceptual framework is proposed in which the artificial reef effect of turbine foundations and the operational noise of wind turbines jointly influence the acoustic space utilization of vocalizing fish.

1. Introduction

In recent decades, global energy development has increasingly shifted toward decarbonization, driving the rapid expansion of clean energy sectors such as offshore wind power [1,2]. Although offshore wind projects are important for achieving carbon-neutral

energy goals, operational turbines generate underwater noise that can alter coastal soundscapes [3–5]. The cumulative ecological impacts of this anthropogenic noise are increasingly recognized as an important issue in coastal ecology research [6,7].

Offshore wind farms can reshape the acoustic spatial dynamics of fish through the combined effects of physical structures and noise disturbance. Wind turbine foundations may act as artificial reef structures by providing hard substrates and localized habitat complexity within otherwise open offshore areas [8,9]. Lindeboom et al. noted that wind farms, as novel habitats, can facilitate the aggregation of benthos and fishes [10]; similarly, Bicknell et al. observed that fish abundance, biomass, and body size near turbine foundations were higher than those in surrounding waters, with a patchy and clustered distribution [11]. At the same time, operational turbines emit persistent low-frequency noise through mechanical vibration, with additional transient noise during startup phases [12–15]. Under simultaneous multi-turbine operation or small turbine-spacing layouts, cumulative noise superposition may alter the localized soundscape [5], thereby influencing soniferous fishes that rely on acoustic signals for courtship, communication, and predator defense [16–18].

Assessing the effects of offshore wind farms on fish dynamics remains challenging because conventional sampling methods are often constrained within core wind-farm zones [19]. Submarine cables, foundation structures, and navigation restrictions can limit the use of traditional fishery surveys such as bottom trawling, although fishing exclusion may also promote the aggregation of higher-trophic-level fishes [20]. In addition, capture-based sampling provides only point-in-time observations and cannot easily capture dynamic responses to fluctuating noise levels or transient operational events. Passive acoustic monitoring (PAM) provides a non-intrusive approach for tracking the vocal activity of soniferous organisms [21–23]. By recording bioacoustic signals from vocal taxa such as Sciaenidae, PAM can provide information on temporal variation in vocal activity and habitat use [24–26]. Compared with active acoustics or visual surveys, PAM can operate under adverse sea states and at night, providing continuous monitoring data for the underwater soundscape [27,28].

This study deployed a passive acoustic sensor array within the core zone of the Yangjiang Offshore Wind Farm, Guangdong Province, China. By first establishing regional fish assemblage information from trawl survey data and then comparing short-term variation in detected fish-call activity across two turbine-spacing scenarios and during a turbine startup sequence, we evaluated the utility of PAM as a non-intrusive indicator of soundscape-associated changes in putative soniferous fish activity. We further examined the potential interaction between foundation-associated habitat structure and operational noise to develop a testable conceptual framework for future ecological monitoring in offshore wind farms.

2. Materials and Methods

2.1. Study Area

The study area is situated in the coastal waters off Yangjiang, Guangdong Province, in the northern South China Sea (Figure 1). It is one of the largest offshore wind farm clusters in Asia and is characterized by extensive planned capacity and diverse turbine configurations. Bathymetry across this region ranges from 22 to 32 m. To date, 270 wind turbines spanning Phases 1 through 5 have been commissioned. These installations include multiple foundation designs, such as monopiles, rock-socketed jackets, monopile-composite buckets, and floating foundations, thereby adding structural complexity to the underwater environment. As shown by the fishery resource survey described below, this marine area supports abundant fishery resources and provides habitat for several soniferous taxa, including Sciaenidae [29]. The present monitoring stations were deployed adjacent to the

outermost turbine of the Phase IV site, which operates at a mean water depth of 28 m and contains a large-scale array of 7 MW wind turbines. The monitoring area for this observation is in the vicinity of $111^{\circ}39'48.80''$ E, $21^{\circ}18'12.07''$ N.

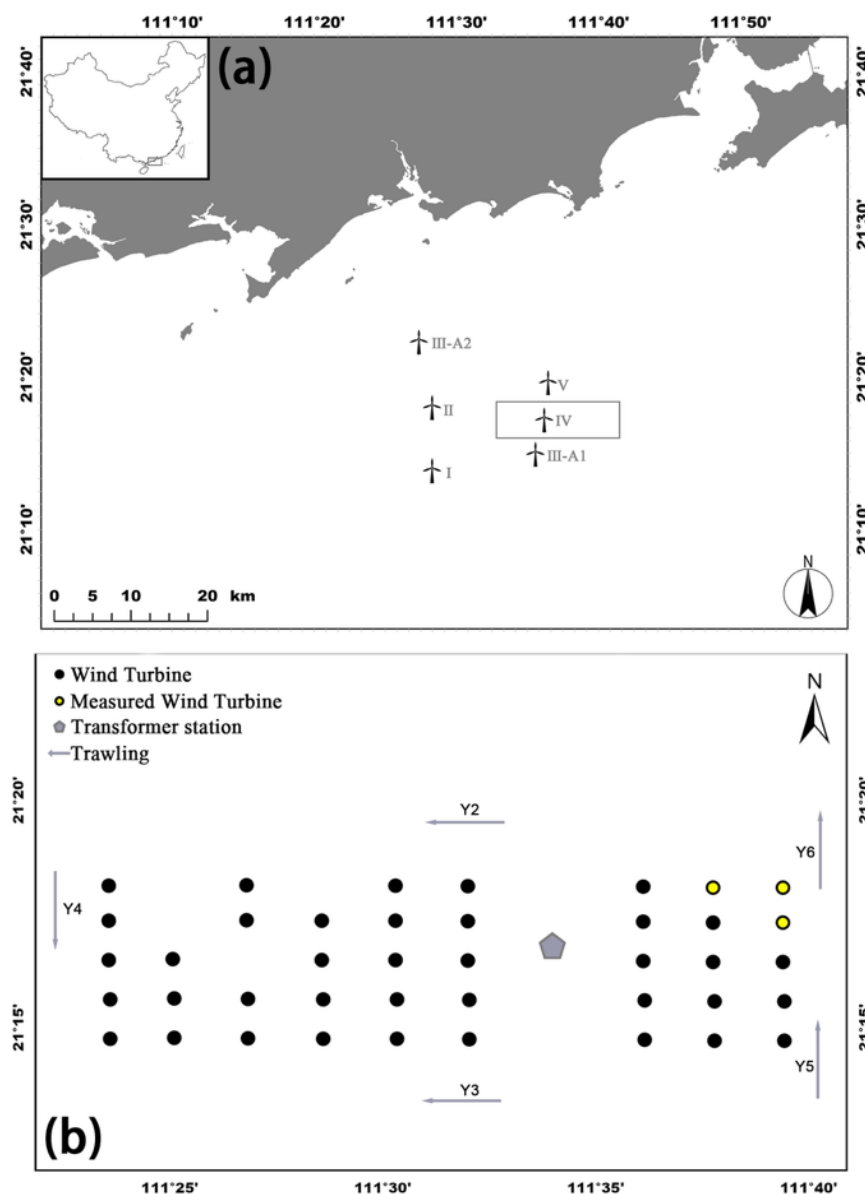


Figure 1. Geographical location of the study area. (a) Schematic map of the Yangjiang offshore wind farm cluster, highlighting Phase IV as the designated survey area; (b) spatial layout of passive acoustic monitoring (PAM) and trawl survey locations; yellow dots indicate the monitored wind turbines, while gray arrows denote the trawl survey transects.

2.2. Fishery Resource Survey

To obtain baseline information on regional fish community composition and to provide biological context for the potential taxonomic sources of acoustic signals detected by PAM, trawl-based fish assemblage data were collected from 1 to 4 August 2024. The trawl data were used as regional biological reference information for interpreting the PAM recordings. Sampling protocols followed the Specifications for Oceanographic Survey Marine Biological Survey (GB12763.6-2007) and relevant technical evaluation guidelines [30]. As illustrated in Figure 1b, six monitoring stations (Y1–Y6) were established for the capture survey, with station Y1 designated as a distant reference station (starting coordinates: $21^{\circ}26'51.95''$ N, $111^{\circ}29'18.68''$ E). Sampling operations used a bottom trawl with a net mouth width of 4.0 m

and a cod-end mesh size of 20 mm × 20 mm. The average trawling speed at each station was maintained at 3 kn (approximately 5.556 km/h), with a continuous tow duration of 0.5 h per station. After capture, fish samples were weighed on board to record the total catch mass and then transported to the laboratory for taxonomic identification and quantitative analysis. For each taxon, species identity, wet mass, and individual abundance were recorded. Catch composition, catch rate, and fishery resource density were subsequently calculated to provide regional fish assemblage information for interpreting the potential biological sources of the acoustic signals detected by PAM.

2.3. Passive Acoustic Monitoring System and Data Collection

To evaluate short-term variation in fish-call activity under different operational soundscape conditions, an integrated acoustic sensing and monitoring framework was established. Acoustic data were acquired using three autonomous hydrophones (SoundTrap ST300, Ocean Instruments, Auckland, New Zealand) with a nominal frequency response of 20 Hz to 60 kHz (± 2 dB). The sampling rate was set to 48 kHz, and the recording mode to continuous recording. Precise spatial positioning and relative distance were determined using a GPS unit (A8, Shenzhen Zhuolin Technology Co., Ltd., Shenzhen, China) and a laser rangefinder (SW-1500B, SNDWAY Co., Ltd., Dongguan, China). Concurrent environmental parameters were recorded using an ultrasonic depth sounder (Hondex PS-7, Honda Electronics Co., Ltd., Toyohashi, Japan) and a digital anemometer (Qingdao MeiQing Electronics Co., Ltd., Qingdao, China). At each station, stationary moored passive acoustic monitoring was conducted. Each hydrophone was deployed using a bottom-weighted mooring system, with a subsurface buoy maintaining the hydrophone in a vertically suspended position in the water column. A miniature data logger (DST milli-F, Star-Oddi, Gardabaer, Iceland) was attached to each hydrophone to monitor ambient water temperature and deployment depth in real-time (accuracy: ± 0.1 °C, $\pm 0.5\%$ full scale [FS]).

After deployment, the research vessel moved away from the monitoring station, and all engines and non-essential power supplies were shut down to minimize vessel-related self-noise. Remaining non-target sounds, including passing vessels and near-field collision noise, were screened during subsequent quality control.

To investigate spatial variation in detected fish-call activity within the offshore wind farm, hydrophones were deployed along distance-gradient transects on 2 September 2025, from 14:00 to 17:30, under two representative turbine-spacing scenarios: a 550 m spacing layout and a 1300 m spacing layout (Figure 2 and Table 1). For each scenario, three monitoring stations were distributed at equidistant intervals along the transect, with P1–P3 assigned to the 550 m turbine spacing and P4–P6 assigned to the 1300 m turbine spacing. To assess fish-call activity during a turbine startup event, three additional monitoring stations (C1–C3) were established adjacent to a single outermost turbine on 3 September 2025, from 13:30 to 15:00. This setup was designed to capture short-term changes in the physical sound field and detected fish-call rates as the turbine transitioned from a resting state to startup and subsequently toward a low-power or stabilized operational state. As depicted in Figure 2, all monitoring stations were configured with a bottom-suspended counterweight and a subsurface buoy positioned 2 m above the hydrophone. The deployment depth of all horizontal monitoring stations was standardized at 18 m, a depth relevant to benthic and demersal soniferous fishes. Continuous recording durations at all stations exceeded 90 min, and a 60 min representative segment was used for comparative analysis.

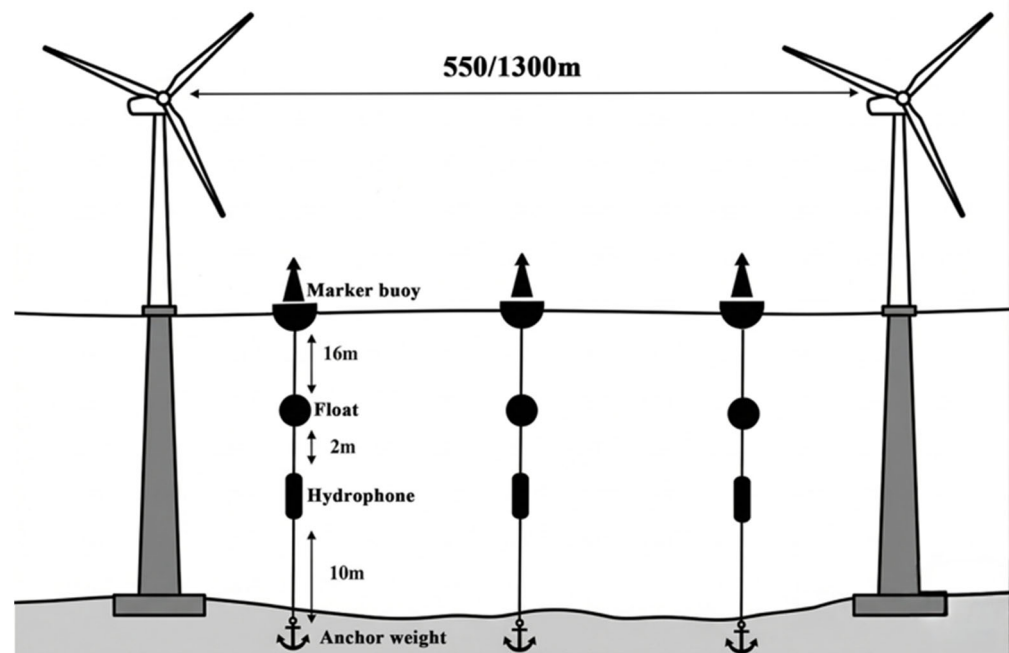


Figure 2. Deployment schematic of the underwater passive acoustic monitoring (PAM) system across different turbine-spacing configurations.

Table 1. Spatial layout and environmental parameters of the monitoring stations.

Monitoring Scenario	Monitoring Station	Relative Distance (m)	Average Wind Speed (m/s)	Average Water Temperature (°C)
Turbine spacing 550 m	P1	110	8.2	28.4
	P2	270	8.2	28.4
	P3	450	8.2	28.4
Turbine spacing 1300 m	P4	320	6.9	28.4
	P5	700	6.9	28.4
	P6	1020	6.9	28.4
Transient startup noise	C1	120	3.0	28.5
	C2	400	3.0	28.5
	C3	620	3.0	28.5

Note: The horizontal distance r was measured from the center of the left turbine foundation.

2.4. Acoustic Signal Processing and Fish-Call Detection

The acquired underwater recordings were initially imported into dBWav (Ocean Instruments, New Zealand) for pre-processing. All segmented epochs were manually screened to exclude data affected by biological collisions, mooring-related knocks, or transient acoustic anomalies from passing vessels. Recordings were first band-pass filtered between 10 and 5000 Hz using a fourth-order Butterworth filter for broad spectrogram visualization and to reduce low-frequency turbine noise and high-frequency background noise outside the analysis range. The filtered signals were then visualized as spectrograms using the short-time Fourier transform (STFT). The STFT parameters were set as follows: the Hamming window was used, the Fourier transform length was 2048 points, and the window overlap rate was set to 75%. Acoustic amplitudes were converted to sound pressure levels referenced to 1 μ Pa using the manufacturer-provided hydrophone sensitivity. For

each monitoring station, a representative 60 min recording was extracted and uniformly segmented into 120 sequential analysis epochs of 30 s each. Time-series data of root-mean-square sound pressure levels (SPLrms) and peak sound pressure levels (SPLpeak) were calculated and exported for subsequent analysis.

Spectrogram-based analysis of putative fish acoustic signals was conducted using Adobe Audition 2025 (Adobe Inc., San Jose, CA, USA) and MATLAB (R2023b). For fish-call detection and spectral characterization, the analysis band was defined as 200–2000 Hz based on the dominant frequency ranges reported for Sciaenidae vocalizations in previous studies. A single fish-call event was defined as an isolated pulse or pulse train clearly separated from adjacent events in both waveform and spectrogram views. Candidate fish-calls were selected based on clear pulse-like temporal structure, clearly distinguishable from the surrounding background noise, and energy concentrated within the predefined fish-call frequency band.

Key acoustic parameters, including inter-pulse interval (IPI), signal duration, peak frequency (PF), and center frequency (CF), were extracted through manual segmentation. PF was defined as the frequency component with the maximum sound level within the call spectrum. CF was defined as the energy-weighted centroid frequency within the predefined fish-call analysis band of 200–2000 Hz. By comparing CF and PF and visually inspecting both waveforms and spectrograms, we characterized the temporal pulse patterns, broadband features, and spectral energy distribution of the putative fish-calls.

Given the substantial interference from turbine mechanical noise, a two-step quality control procedure was applied to improve the reliability of call counting and classification. First, an independent researcher who was not involved in the primary analysis randomly sampled 30% of the audio segments for blind cross-validation. The total number of candidate call events yielded a relative error rate of less than 5% between observers, indicating good repeatability of the manual counting procedure under the adopted selection criteria. Second, permutation entropy (PE) was used as an auxiliary descriptor to support the discrimination between pulse-like candidate fish-calls and irregular noise events [31,32]. In this study, a high-resolution sliding root-mean-square (RMS) envelope with a 5 ms window was extracted, and the PE value (H) was computed based on the assigned embedding dimension $M = 4$.

2.5. Statistical Analysis

All statistical analyses were conducted using SPSS Statistics (Version 26.0, IBM, Armonk, USA) to explore variation in fish acoustic activity across turbine-spacing layouts and operational states and to examine its relationship with measured sound pressure levels and wind conditions. To compare fish-call activity between the two turbine-spacing scenarios, vocal events were aggregated into 10 min time bins and compared using the non-parametric Mann–Whitney U test. Changes in fish-call detections during the turbine startup event and the association between wind speed and underwater sound pressure level were evaluated using Spearman's rank correlation analysis. Statistical significance was assessed at $p < 0.05$.

3. Results

3.1. Trawl Survey Data

The conventional fishery resource survey recorded 37 fish species from 27 families and 7 orders. Perciformes was the dominant order, comprising 22 species from 13 families and accounting for 59.46% of the total recorded species (Table S1). Clupeiformes (10.81%) and Anguilliformes (8.11%) were also important components of the regional assemblage. These results indicate that the wind farm area supports a diverse fish community during its operational phase.

Fish density within the wind farm area exhibited spatial heterogeneity across survey stations. As shown in Table 2, the mean numerical density among the five stations inside or near the wind farm (Y2–Y6) was 29,184.47 ind./km², with the highest value recorded at station Y3 (33,425.90 ind./km²). In terms of biomass, the mean biomass density across these five stations was 587.67 kg/km², with the highest value recorded at station Y5 (688.98 kg/km²). Station Y1, serving as a distant background reference station, showed the lowest values for both numerical density (22,112.52 ind./km²) and biomass density (452.26 kg/km²). Specifically, the numerical density at Y3 was approximately 51.1% higher than that at Y1, while the biomass density at Y5 exceeded the Y1 baseline by approximately 52.3%.

Table 2. Fish resource density in the Phase IV area of the Yangjiang Offshore Wind Farm.

Survey Station	Numerical Density (ind./km ²)	Biomass Density (kg/km ²)
Y1	22,112.52	452.26
Y2	31,245.81	582.68
Y3	33,425.90	557.75
Y4	24,426.62	475.52
Y5	25,969.35	688.98
Y6	30,854.67	633.43

As derived from the Index of Relative Importance (IRI) calculations presented in Table 3, the study area was characterized by five principal species. *Saurida elongata* was the only dominant species (IRI = 1223.98). *Johnius belangerii*, a member of Sciaenidae, was categorized as a major species with an IRI value of 560.55. The frequency of occurrence (F) for *J. belangerii* reached 100% across all survey stations, indicating the broad spatial distribution of this soniferous taxon within the wind farm area. These results provided biological context for interpreting fish acoustic signals detected by PAM.

Table 3. Population parameters of the dominant fish species within the Phase IV area of the Yangjiang Offshore Wind Farm.

Species	N (%)	W (%)	F (%)	IRI
<i>Saurida elongata</i>	3.53	8.71	100.00	1223.98
<i>Decapterus maruadsi</i>	2.12	6.21	100.00	832.98
<i>Siganus fuscescens</i>	2.70	3.37	100.00	606.94
<i>Johnius belangeri</i>	2.31	3.29	100.00	560.55
<i>Ilisha elongata</i>	2.50	2.55	100.00	505.46

Note: N: numerical percentage; W: biomass percentage; F: frequency of occurrence; IRI: Index of Relative Importance. The IRI is a composite metric integrating abundance, biomass, and spatial prevalence, thereby circumventing the bias inherent in single-indicator assessments to accurately evaluate species dominance within the community. Species with an IRI > 1000 are classified as dominant species, whereas those with an IRI between 500 and 1000 are categorized as major species. Together, these constitute the dominant species assemblage.

3.2. Acoustic Signals of Putative Soniferous Fish

Based on the existing literature on Sciaenidae acoustic signatures and the regional trawl survey data, multiple categories of putative soniferous fish-calls were extracted from the PAM recordings. As illustrated in Figure 3, distinct bands of bioacoustic signals were present within the study area. The first signal cluster showed peak frequencies (PFs) concentrated at approximately 400–500 Hz, whereas center frequencies (CFs) were distributed mainly between 400 and 800 Hz. The broader and generally higher CF distribution indicates that although the maximum amplitudes of these calls occurred at relatively low frequencies, their overall spectral structure contained broadband high-frequency energy

or harmonic components. Because CF represents the energy-weighted centroid across the analysis band, secondary amplitude peaks or broadband energy spread in the mid-to-high frequency range elevated the overall CF values. In the time domain, these signals primarily appeared as single or infrequent transient knocks (Figure 4c).

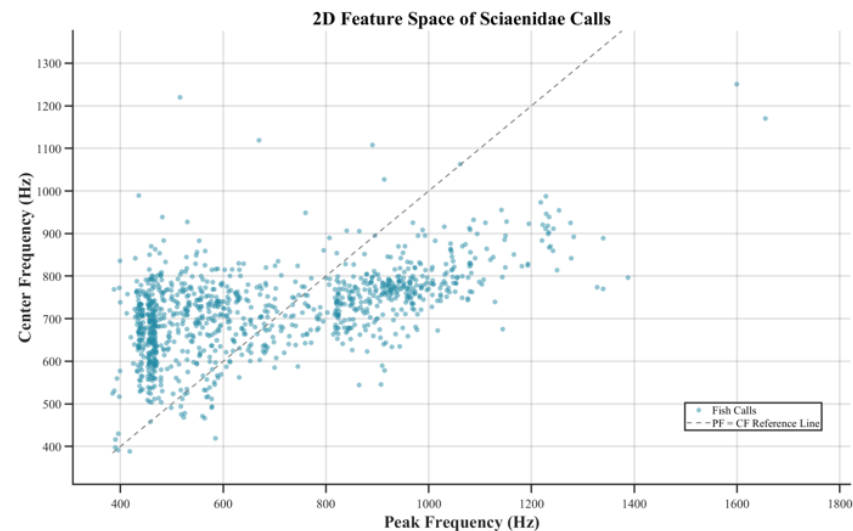


Figure 3. Two-dimensional distribution of acoustic characteristics (center frequency and peak frequency) for fish vocalization signals.

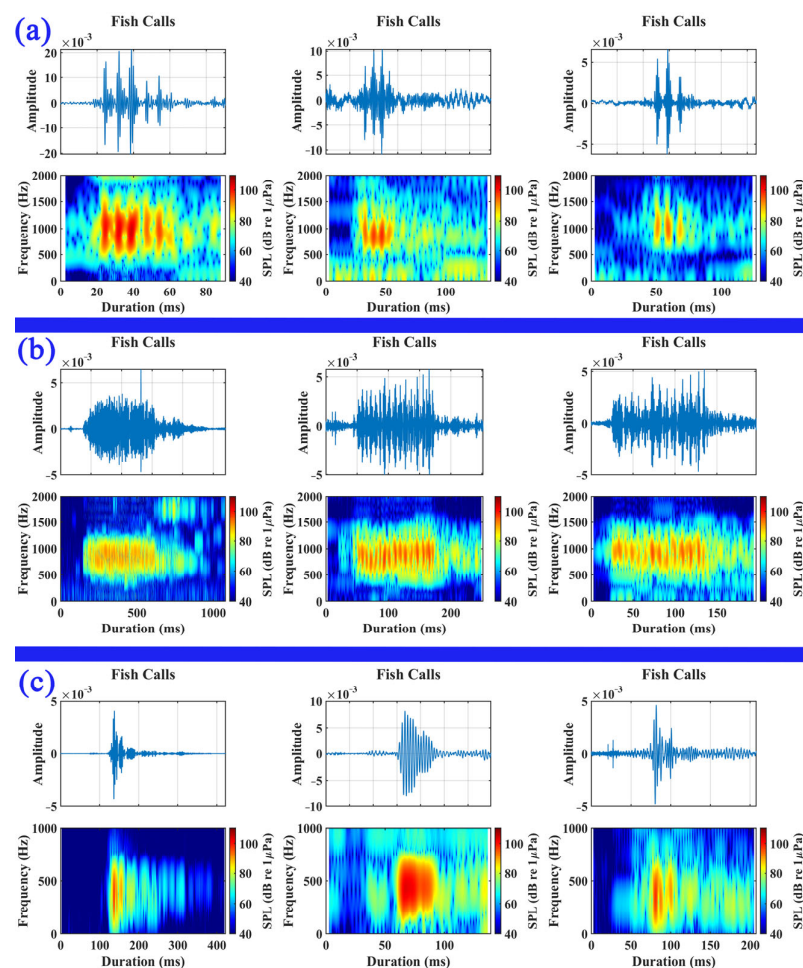


Figure 4. Comparison of time-domain and frequency-domain characteristics of fish vocalization signals. (a) represents a short sound at a higher frequency; (b) represents a long sound at a higher frequency; (c) represents a short sound at a lower frequency.

The second signal cluster showed an upward shift in the frequency domain, with PFs concentrated between 800 and 1000 Hz and CFs clustered around 750–850 Hz. This cluster exhibited multiple time-domain morphologies, including sparse broadband pulse trains (Figure 4a) and sustained pulse sequences lasting up to 800 ms (Figure 4b). These observations indicate that multiple acoustic signal types of putative soniferous fish occurred in the wind-farm soundscape. The detected calls showed clear temporal variability within similar frequency ranges, ranging from isolated short pulses to prolonged pulse trains. Spectrogram-based comparisons further showed that the main energy of these signals was concentrated in relatively high-frequency bands, where turbine-related mechanical noise was less prominent than in the lower-frequency range. Accordingly, these signals were interpreted as putative soniferous fish-calls in the present study.

3.3. Spatial Variation in Fish Vocal Activity Under Different Turbine Spacing

The measured noise levels differed between the two turbine-spacing scenarios (Table 4). The 550 m spacing layout showed higher acoustic levels, with SPL_{peak} values ranging from 145.6 to 151.6 dB re 1 μ Pa and SPL_{rms} values ranging from 114.5 to 116.0 dB re 1 μ Pa. In contrast, the 1300 m spacing layout showed lower acoustic levels, with SPL_{peak} values ranging from 132.3 to 139.6 dB re 1 μ Pa and SPL_{rms} values ranging from 107.7 to 108.7 dB re 1 μ Pa. Relative to the background noise baseline of approximately 107.0 dB re 1 μ Pa, the increase in SPL_{rms} was greater in the 550 m spacing layout than in the 1300 m spacing layout, indicating a higher operational noise environment under the 550 m turbine-spacing scenario. This pattern may reflect the cumulative contribution of noise from adjacent turbines.

Table 4. Distribution of sound pressure levels at monitoring stations under different turbine-spacing configurations.

Turbine Spacing	Monitoring Station	SPL _{peak} (dB re 1 μ Pa)	SPL _{rms} (dB re 1 μ Pa)	Relative Increase over Background (dB)
550 m	P1	145.6	114.5	7.5
	P2	151.6	116.0	9.0
	P3	149.8	115.3	8.3
1300 m	P4	138.7	108.3	1.3
	P5	132.3	107.7	0.7
	P6	139.6	108.7	1.7

Note: SPL_{peak} denotes the peak sound pressure level, and SPL_{rms} denotes the root-mean-square sound pressure level. The reference pressure is 1 μ Pa. The ambient background noise baseline across the study area is approximately 107.0 dB re 1 μ Pa.

Fish-call detections differed between the two monitored turbine-spacing scenarios (Figure 5). The 1300 m transect recorded a total of 394 candidate bioacoustic signals, whereas fewer calls were detected along the 550 m transect. When vocal events were aggregated into 10 min bins and compared using the Mann–Whitney U test, detections were higher under the 1300 m spacing scenario than under the 550 m spacing scenario ($U = 3.50$, $Z = -5.01$, $p < 0.05$).

Within the 550 m spacing layout, the central station P2 had the lowest call count, with 28 detections over the 60 min observation period. Within the 1300 m spacing layout, the central station P5 had the highest call count, with 181 detections. These patterns coincided with higher measured SPLs in the 550 m layout and lower SPLs in the 1300 m layout.

Combining the physical soundscape data with fish-call detection patterns, the 550 m transect showed higher background sound levels and lower detected call activity, whereas the 1300 m transect showed lower sound levels and higher detected call activity. The

6.46-fold difference in detections between stations P5 and P2 is consistent with the hypothesis that lower noise levels within a wind farm may support greater detectable fish vocal activity or reduce masking.

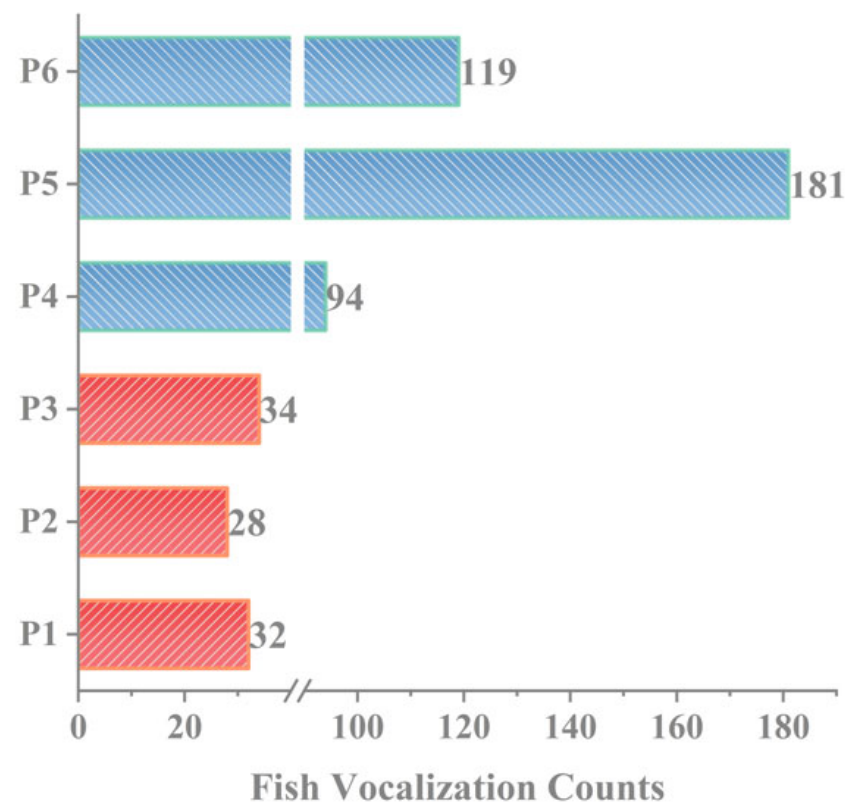


Figure 5. Comparison of fish vocal activity under different turbine-spacing configurations. Monitoring stations P1–P3 correspond to the 550 m spacing, while stations P4–P6 correspond to the 1300 m spacing.

3.4. Fish-Call Detections During Turbine Startup

The physical acoustic field data in Figure 6a captured the non-stationary energy pulses generated during wind turbine startup. During the initial startup phase (0–5 min), the overall SPL at each station showed a gradual upward trend. Acoustic energy then increased rapidly between 5 and 10 min, with a clear distance-attenuation pattern. Station C1, located closest to the turbine, recorded the highest peak SPL, reaching 133.0 dB re 1 μ Pa, approximately 23 dB above the pre-operational baseline. As propagation distance increased, transient peak values at stations C2 and C3 attenuated to 128.7 dB re 1 μ Pa and 126.2 dB re 1 μ Pa, respectively. From the 11th minute onward, transient energy declined and the acoustic field gradually returned toward background levels.

Detected fish-call rates declined during the transient increase in acoustic energy associated with turbine startup (Spearman's, $\rho = -0.714$, $p < 0.05$). As shown in Figure 6b, fish-call counts across the monitoring stations decreased as SPL rose, and detections temporarily reached zero at several stations during the highest-noise interval. Notably, station C1, situated closest to the turbine, showed an approximately 5 min period without detected fish-calls. During the final phase of the turbine startup event, as sound levels stabilized or declined, fish-call detections recovered across all stations, with station C1 reaching up to 8 calls/min between the 12th and 14th minutes.

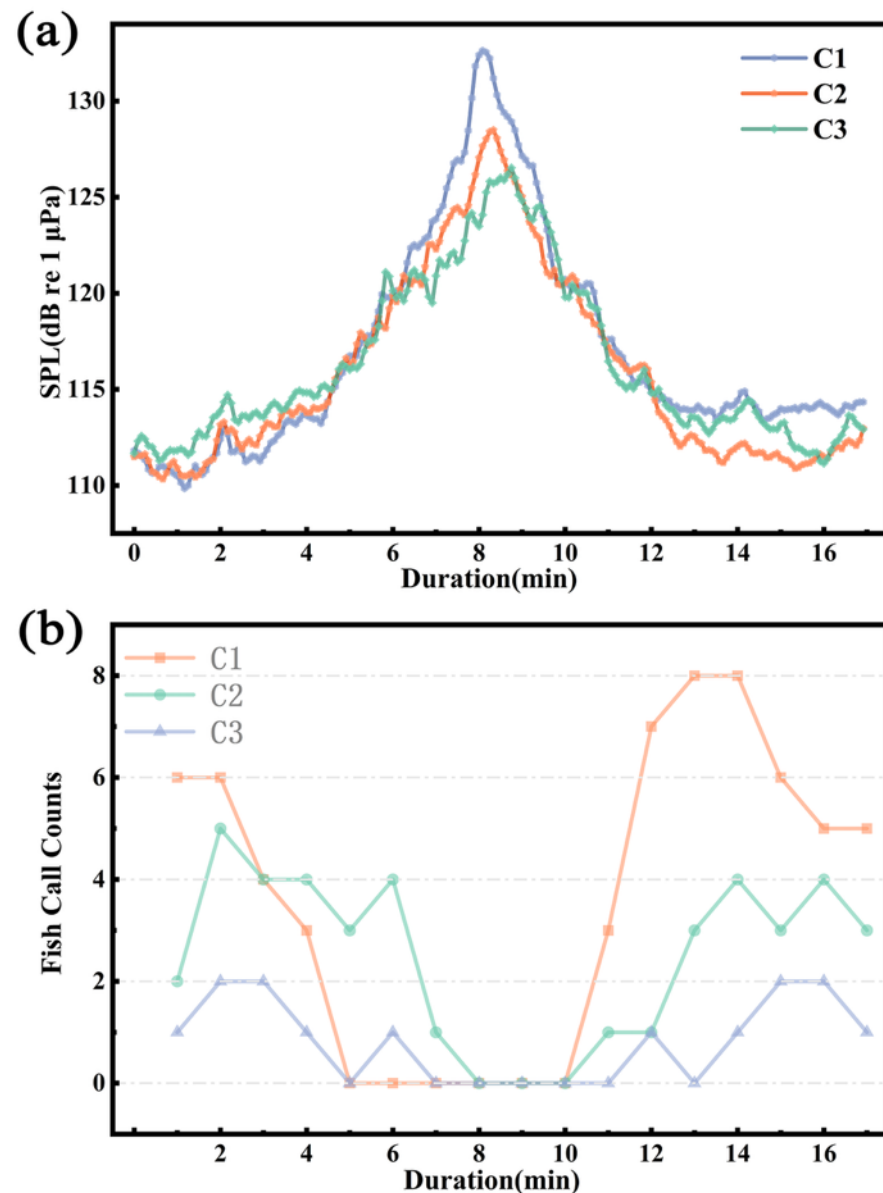


Figure 6. Physical sound field and fish vocal activity during the turbine startup transient process. (a) Total sound pressure levels (SPL) at different distances during turbine startup; (b) fish vocalization rate (calls per minute) at different distances during turbine startup.

4. Discussion

4.1. PAM Efficacy and Acoustic Signatures of Soniferous Fishes

Because intrusive survey methods such as traditional bottom trawling are largely constrained within offshore wind farms, the dynamic distribution of ecological communities in these waters remains difficult to evaluate [19]. The present study integrated regional fish assemblage data from trawl surveys with internal PAM monitoring to interpret the possible taxonomic sources of soniferous fish-calls. The soniferous taxa identified from the trawl samples provided an important biological reference for interpreting the putative fish acoustic signals detected by PAM. The bottom trawl inventory (Table S2) indicated a diverse regional soniferous community, including *Johnius belangerii*, which exhibited a 100% frequency of occurrence, other Sciaenidae species such as *Argyrosomus argentatus*, *Pennahia argentata*, and *Nibea albiflora*, and soniferous taxa from Terapontidae such as *Pelates quadrilineatus*.

The dominant frequency of fish vocalizations often correlates negatively with body size and swim bladder morphology in soniferous fishes [33–35]. Based on the existing literature and the regional trawl inventory, the low-frequency signal cluster could plausibly correspond to larger Sciaenidae or other demersal soniferous fishes, whereas the higher-frequency cluster could involve smaller Sciaenidae or other regional soniferous taxa. The second signal cluster showed higher-frequency characteristics, frequent occurrence, and a relatively broad frequency distribution. Based on its spectral features and the trawl survey records, this cluster was likely associated with dominant Sciaenidae species such as *J. belangerii*. Furthermore, the widespread occurrence of *P. quadrilineatus* in the trawl inventory suggests that this species may also contribute to some broadband pulse signals. Together, these acoustically distinct signal types indicate a heterogeneous soundscape produced by multiple soniferous fish taxa within the benthic zone of the wind farm.

Within similar frequency bands, this study detected contrasting time-domain vocal morphologies, including single or sparse short pulse signals and prolonged continuous pulse sequences. In the modified acoustic habitat of a wind farm, these signal types may reflect behavioral-state variation under different soundscape conditions. In natural environments, brief and irregular knocks produced by fishes are often associated with contact communication, group cohesion, or localized territorial interactions. In contrast, prolonged and dense pulse trains are widely reported in Sciaenidae and are commonly linked to reproductive activity and male courtship behavior [36,37]. Within the acoustically modified habitat of an offshore wind farm, these vocal patterns may also be influenced by operational turbine noise and other disturbance stimuli. The coexistence of similar-frequency signals with distinct temporal pulse structures suggests that benthic soniferous fishes may express different acoustic signal types under varying behavioral or environmental conditions. These results highlight the potential value of soniferous fishes as acoustic indicators for assessing biological responses to changing underwater soundscapes in offshore wind farms.

4.2. Fish-Call Activity Associated with Operational and Transient Noise

Using short-term spatial arrays and high-temporal-resolution dynamic analysis, this study observed clear associations between operational sound fields and detected fish-call activity. Both continuous operational noise and transient startup noise coincided with changes in call detections, suggesting that PAM can capture rapid soundscape-associated variation in the acoustic activity or detectability of soniferous fishes. During the continuous operation phase, turbine layout may influence the distribution of underwater sound levels through the combined propagation and superposition of turbine-generated noise. Under the 550 m layout, measured SPLs were higher and detected call counts were lower, especially at the central station. For soniferous fishes such as Sciaenidae, exposure to elevated underwater noise may interfere with acoustic communication through masking and may also induce auditory or physiological stress when exposure is sufficiently intense or prolonged. Previous studies have shown that noise exposure can impair brain function and equilibrium in small yellow croaker (*Larimichthys polyactis*) [38] and can alter physiological indicators, including adrenaline, blood glucose, thyroid hormones, and lactic acid, in large yellow croaker (*Larimichthys crocea*) [39]. Acoustic masking may further reduce the efficiency of prey detection, predator avoidance, mate selection, and reproductive communication [40,41]. In the present study, the 1300 m turbine-spacing layout showed lower measured SPLs than the 550 m layout, and the central station of the 1300 m transect recorded the highest fish-call detections, exceeding those at the central station of the 550 m transect by 6.46-fold. These patterns suggest that areas with lower operational noise may provide more favorable acoustic conditions for soniferous fishes. Therefore, in addition to engineering considerations such as wake effects and submarine cable layout, underwater

noise conditions should be considered in the ecological assessment and micro-siting of offshore wind farms, particularly in areas that overlap with spawning grounds, feeding habitats, or other ecologically sensitive habitats for soniferous fishes. These findings further suggest that turbine micro-siting strategies that reduce cumulative operational noise may help maintain low-noise spaces or acoustic corridors within offshore wind farms.

Beyond the spatial patterns associated with continuous operational noise, the transient pulses generated during turbine startup constituted a strong short-term acoustic disturbance. The dynamic recordings collected during turbine startup showed a marked reduction in detected fish-call activity across the monitored range of 620 m. Compared with the relatively steady low-frequency noise during continuous operation, the transient broadband increases generated during startup may represent a stronger short-term acoustic disturbance to fishes [42,43]. Previous studies have also suggested that intermittent noise can elicit stronger physiological stress responses than continuous noise exposure [44]. In the present study, the temporary reduction in detected calls during the startup phase may reflect a combination of acoustic masking, short-term movement away from the hydrophone detection range, or the active suppression of vocal behavior. These observations indicate that turbine startup events may be associated with short-term disruption to detectable fish acoustic activity.

4.3. Ecological Response Hypothesis

Most studies suggest that the underwater structures of wind turbines can function as artificial reefs, forming local benthic aggregation zones [45]. The present short-term monitoring results indicate that ecological effects within wind farms are likely influenced by a dual mechanism: the habitat benefits associated with turbine foundations and scour protection, and the potential disturbance or masking effects of operational noise. Foundation structures may provide shelter, foraging opportunities, and localized hydrodynamic modification, which can enhance habitat suitability for fish, whereas turbine-generated underwater noise may impose communication costs or disturbance risks. We therefore propose a testable hypothesis that fish acoustic space use near turbines is shaped by a dynamic trade-off between these positive and negative effects.

The synchronous acquisition of wind speed and SPL data in this study provides evidence for a relationship between wind conditions and underwater sound levels. As illustrated in Figure 7, underwater noise levels within the wind farm exhibited a significant positive correlation with ambient wind speed (Spearman's $\rho = 0.68$, $p < 0.05$), indicating that stronger wind conditions were associated with higher operational noise levels. Frid et al. suggested that animals may balance external disturbance risk against the immediate benefits of foraging and sheltering [46], thereby adjusting habitat utilization strategies through behavioral plasticity [47]. In this context, high-wind and high-noise operational conditions may increase acoustic disturbance and communication masking for soniferous fishes, potentially reducing their use of areas close to turbine foundations despite the habitat benefits provided by these structures. Such a trade-off may help explain the observed reduction in detected fish-call activity under higher-noise conditions.

When wind speeds declined and turbines returned to a relatively stable low-noise operational state, the balance between habitat benefits and acoustic disturbance may have shifted again. In this study, station C1, located closest to the turbine, recorded 140 fish-call detections during the 20 min period before startup. After the transient startup noise had subsided and the turbine returned to a stable low-noise state, fish-call detections did not remain suppressed; instead, they increased to 151 detections during the following 20 min period. This rapid recovery in detected acoustic activity suggests that the reduction in fish-call detections during startup was temporary. From a bioacoustic perspective, the

post-startup increase in call detections may reflect the re-establishment of favorable acoustic conditions once transient noise disturbance decreased [48–50]. These results suggest that under lower-noise conditions, the habitat benefits associated with turbine foundation structures may again become more apparent, allowing detectable fish acoustic activity to recover shortly after noise abatement. Such short-term variation in call detections indicates that benthic soniferous fishes may adjust their acoustic activity in response to dynamic changes in the wind-farm soundscape.

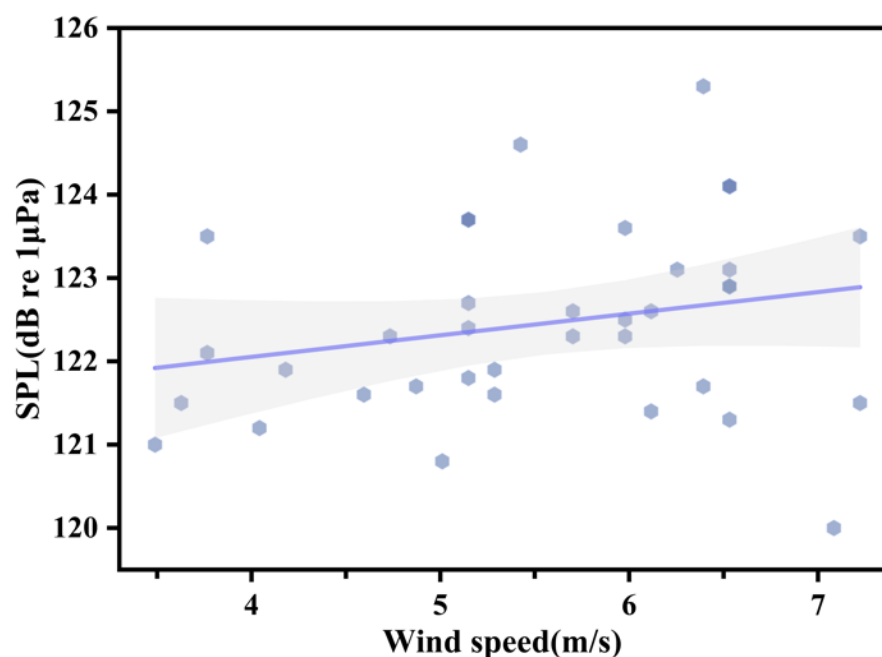


Figure 7. The relationship between underwater noise generated by fan operation and wind speed.

4.4. Future Prospects for Integrated Monitoring

The present study demonstrates the value of PAM for tracking the acoustic activity of soniferous fishes during turbine operation and for capturing short-term changes in fish-call detections under different soundscape conditions. As a non-intrusive monitoring tool, PAM primarily records actively vocalizing species and their relative acoustic activity, making it particularly suitable for assessing changes in detectable bioacoustic patterns within operational wind farms. Combining PAM-derived metrics with fishery resource data, environmental measurements, and turbine operational information can further strengthen ecological interpretation and provide a more comprehensive view of fish responses within offshore wind-farm habitats. Future monitoring can integrate PAM with complementary technologies such as acoustic Doppler current profilers (ADCPs), high-frequency imaging sonar, stereo-PAM localization, acoustic telemetry, and environmental DNA (eDNA) to establish a multidimensional cross-validation framework. Specifically, this framework aims to integrate multimodal data: (1) utilizing PAM data to track the dynamic vocalization rhythms and behavioral stress responses of organisms; (2) utilizing biological data, such as that from conventional fishing or environmental DNA, to confirm species composition and the relative abundance of non-vocalizing fish; (3) utilizing spatial localization data, such as acoustic telemetry, to track the detailed three-dimensional escape trajectories of fish in response to transient noise disturbances. Cross-seasonal and long-term monitoring is also needed to distinguish diel, seasonal, reproductive, and operational drivers of fish-calling activity. Controlled acoustic exposure experiments would further help determine whether prolonged exposure to continuous turbine noise induces temporary threshold shifts (TTS),

habituation, or persistent changes in vocal behavior. Such advances will provide a stronger basis for ecological risk assessment and the adaptive management of offshore wind farms.

5. Conclusions

This study employed passive acoustic monitoring (PAM) to investigate the acoustic activity of soniferous fishes and its association with turbine operational noise in the Yangjiang Offshore Wind Farm. The results revealed the presence of putative fish vocal signals likely associated with Sciaenidae and other soniferous taxa and demonstrated the utility of PAM for capturing short-term variation in fish acoustic activity within offshore wind farms. Differences in underwater noise levels and fish-call detections were observed between turbine-spacing layouts. Compared with the 550 m spacing layout, the 1300 m spacing layout showed lower measured noise levels and higher fish-call detections, suggesting that turbine spacing may influence the balance between operational noise exposure and detectable bioacoustic activity. In addition, transient noise generated during turbine startup was associated with a temporary reduction in detected fish-call activity, followed by recovery after noise levels returned to a relatively stable state. Overall, these findings suggest that fish acoustic activity within offshore wind farms may be shaped by the combined effects of foundation-associated habitat structure and turbine-generated underwater noise. This study provides a PAM-based perspective for assessing the ecological implications of offshore wind farms and for incorporating underwater acoustic conditions into ecologically informed wind-farm spatial planning.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/fishes11080451/s1>, Table S1. Composition of fish communities in the survey area; Table S2. List of swimming animal species.

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