

Contents lists available at ScienceDirect

Marine Pollution Bulletin



journal homepage: www.elsevier.com/locate/marpolbul

Monitoring of the physiological responses of marine fishes to construction and operation noise from offshore wind farms *

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ARTICLE INFO

Keywords: Underwater noise Environmental impact assessment Physiological stress Metabolic rate Fisheries Aquaculture

ABSTRACT

With the rapid expansion of offshore wind energy, concerns have emerged regarding its effects on marine organisms. This study evaluated physiological responses of juvenile *Larimichthys crocea* and *Paralichthys olivaceus* to underwater noise from offshore wind farms, including pile driving and turbine operation. Oxygen consumption rate (OCR), osmolality, and catecholamine levels were measured. Compared to controls, *L. crocea* exposed to 24h pile driving noise showed a significantly higher OCR (0.316 vs. 0.225 mg $O_2 g^{-1} h^{-1}$, p < 0.01) and elevated osmolality (271 vs. 224 mOsm kg⁻¹, p < 0.05). In contrast, *P. olivaceus* showed significantly lower OCR (0.105 vs. 0.113 mg $O_2 g^{-1} h^{-1}$, p < 0.01). Catecholamine levels remained unchanged in both species. Notably, these nocturnal species exhibited heightened sensitivity to noise at night. Turbine operation noise elicited no significant physiological responses. These findings emphasize species-specific responses and highlight the need to consider underwater noise in marine ecosystem management.

1. Introduction

With the increasing utilization of marine environments, ambient noise levels in the low-frequency range (below several hundred hertz), detectable by marine organisms, increased by approximately 19 dB re 1 μ Pa between 1950 and 2007 (Frisk, 2012). Furthermore, the climate change induced melting of sea ice has been reported to cause a 16 dB re 1 μ Pa increase in ambient noise levels in the East Siberian Sea within a month (Han et al., 2021). These changes are expected to accelerate in the future with population growth, coastal urbanization, increasing maritime traffic, and expanding marine resource development (Di Franco et al., 2020). As part of the global response to climate change and resource depletion, the development of renewable energy sources has been expanding rapidly, with offshore wind farms (OWFs) emerging as a key alternative (Nicholson, 2024). As of 2023, OWF installations

generate 75.2 GW of energy, accounting for 7.4 % of the total global wind energy capacity (Global Wind Energy Council, 2024). In Korea, both pile driving and turbine operational noise generated during OWF development have been measured off the southwest coast, with reported source levels of 183–184 dB re 1 μ Pa²s for pile driving (Han and Choi, 2022) and a ~20 dB increase in tonal noise near 198 Hz during turbine operation (Yoon et al., 2023).

However, the construction and operation of OWFs introduce various environmental stressors, including underwater noise (from pile driving and turbine operation), magnetic fields, and suspended sediments (Cieślewicz et al., 2025; Xu et al., 2025). Anthropogenic noise can disrupt marine organisms' communication, foraging, orientation, territorial defense, and reproductive activities (Duarte et al., 2021; Siddagangaiah et al., 2024; Kim et al., 2024). It is now globally recognized as a major component of marine noise pollution, prompting governments

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https://doi.org/10.1016/j.marpolbul.2025.118139

Received 25 January 2025; Received in revised form 7 May 2025; Accepted 8 May 2025 Available online 16 May 2025

 $^{^{\}star}\,$ This article is part of a Special issue entitled: 'YES2023' published in Marine Pollution Bulletin.

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and research institutions to assess its environmental impacts and establish regulatory criteria for underwater noise (Bergström et al., 2014; Popper et al., 2014; Southall et al., 2019). In 1998, the National Oceanic and Atmospheric Administration established an international expert panel to study the effects of underwater noise on marine mammals, leading to substantial research efforts in this field (Jerem and Mathews, 2021). However, such effects on fish remain understudied, despite their vast biomass in marine ecosystems and significant role as a food resource for humans.

Research on the effects of underwater noise on fish has focused primarily on behavioral responses, although physiological assessment represents a complementary approach (Duarte et al., 2021). As physiological measures can detect subtle stress responses that may not be evident through behavioral observation, their incorporation could enhance our understanding of noise impacts on fish. Physiological parameters serve as critical indicators of stress in fish, encompassing neuroendocrine regulation, the metabolic rate, and osmoregulatory function (El-Dairi et al., 2024). Catecholamines, such as epinephrine and norepinephrine, modulate cardiovascular and respiratory processes under stress (Reid et al., 1998). Osmoregulation is essential for the maintenance of homeostasis, enabling fish to adapt to varying salinities (Fridman, 2020). As environmental stressors can disrupt the ionic balance, osmolality serves as a physiological indicator of stress responses. Respiratory function is also a crucial determinant of stress, as oxygen consumption reflects metabolic demands and adaptive responses (Sopinka et al., 2016). The respiratory responses of fish to underwater noise have often been assessed using the dissolved oxygen (DO) concentration (Bruintjes et al., 2016b) and/or ventilation rate as a proxy (Nedelec et al., 2016), but reliance on these endpoint-based measures may lead to the overlooking of temporal physiological adjustments. Given the prolonged nature of noise-induced stress, the real-time monitoring of the oxygen consumption rate (OCR) is essential for the elucidation of stress response dynamics and habituation in fish.

This study was conducted to evaluate the physiological responses of *Larimichthys crocea* and *Paralichthys olivaceus*, two marine fish species with high fishery value, to underwater noise exposure during OWF construction and operation. We assessed the physiological responses of the fish to short-term pile driving noise as well as prolonged pile driving and turbine operation noise. Along with our findings, we reviewed the effects of underwater noise, magnetic fields, and suspended sediments on fish metabolic rates. This study aims to provide scientific evidence on the physiological impacts of underwater noise on commercially important fish species, thereby supporting the development of appropriate assessment frameworks for OWF activities.



Fig. 1. (a) Experimental design for the monitoring of fish oxygen consumption rates under underwater noise exposure. (b) The test species (*Larimichthys crocea*, large yellow croaker and *Paralichthys olivaceus*, olive flounder). (c) Sound characteristics of pile driving noise (PD1 and PD2 exposures) and turbine operation noise (TO exposure). (d) Experimental procedure. DO, dissolved oxygen. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Materials and methods

2.1. Experimental design

We modified a closed circulation chamber system developed by Chu et al. (2020) to monitor the physiological changes in fish exposed to underwater noise (Fig. 1a). The system consisted of upper, middle, and lower layers of chambers connected by tubing. Each chamber was 27 cm in diameter and 26 cm in height, with 1-cm-thick transparent acrylic walls, and held ~12.3 L seawater. The upper chamber was continuously supplied with air by a pump (YP-10A, 9 W; Jung Su Industry, Gimhae, South Korea). The middle chamber held the fish and was where respiration occurred, consuming oxygen. To recirculate seawater back into the upper chamber, a return pump (UP500, 50 W; HyubShin Water Design, Seoul, South Korea) was used in the lower chamber. Oxygen consumption by the fish was monitored by calculating the difference in DO concentrations between the upper and lower chambers. Two systems were used per experimental group, with two replicates. For underwater noise exposure, a circular tank (110 cm in diameter and 30 cm in height, with 1-cm-thick opaque white acrylic walls) containing freshwater was equipped with an underwater speaker (LL916C; Lubell Labs Inc., Columbus, OH, USA). The speaker was centrally positioned, with four middle chambers placed around the perimeter.

2.2. Test species

Juvenile large yellow croaker (*L. crocea, n* = 80) and olive flounder (*P. olivaceus, n* = 80) were collected from local fish farms in South Korea (34°43'N, 127°46'E and 36°27'N, 126°29'E, respectively; Fig. 1b). Their mean total lengths were 98 ± 13 and 127 ± 20 mm and their mean wet weights were 16.2 ± 6.3 and 22.3 ± 4.4 g, respectively. The fish acclimated in stock tanks ($0.7 \times 0.4 \times 0.6$ m, holding ~140 L seawater) under laboratory conditions (water temperature = 20 ± 1 °C, salinity = 35 psu, light/dark cycle = 10/14 h) for at least two weeks. To maintain fish fitness, individuals with diseases or significant size differences were regularly isolated and excluded from the experiments. We provided dry floating pellets once daily, except on the day before the experiment to ensure at least 24 h fasting. Following the experiments, which involved blood sample collection for biochemical analysis, the fish were humanely sacrificed with a 2-phenoxyethanol solution (Sigma-Aldrich, Saint Louis, MO, USA).

2.3. Sound characteristics

The original recording of pile driving noise from Nedwell et al. (2003) and onshore wind turbine generator uploaded to Freesound (https://freesound.org/people/HerbertBoland/sounds/114594/) were edited into 1-h track using Audacity 3.0.2 (https://www.audacityteam. org), respectively. The pile driving and turbine operation noise tracks were played back through the underwater speaker connected to an amplifier (PMP550M; Behringer, Willich, Germany), a transformer (AC203E; Lubell Labs Inc.), and a laptop.

The sound pressure level (SPL) was measured at 18 points at a depth of 15 cm in the circular tank of the middle layer using a hydrophone (TC4032, 5–120,000 Hz frequency range, -170 dB re 1 V μ Pa⁻¹ receiving sensitivity; Teledyne RESON, Slangerup, Denmark) connected to a preamplifier (EC6070; Teledyne RESON), with a band-pass filter applied in the frequency range of 100–5000 Hz. The SPL distribution in the tank was contoured using Surfer 8 software (Golden Software, Golden, CO, USA) for the visualization of spatial data (Fig. 1c). The root mean square sound pressure level (SPL_{rms}) of the ambient noise was 130 dB re 1 μ Pa, and this level reached 139 dB re 1 μ Pa during turbine operation noise playback. For reference, the pump was operated continuously for circulation, contributing to the relatively high level of ambient noise. The zero-to-peak sound pressure level (SPL_{z-p}) of the pile driving noise playback was 179 dB re 1 μ Pa. Signal analysis software

(HD-300; Rectuson, Changwon, South Korea) was used to calculate and analyze the SPL_{rms} and SPL_{z-p} values. The waveforms and power spectral densities of the original recordings were analyzed using the PAMGuide package (Merchant et al., 2015) in MATLAB (R2024b; MathWorks, Natick, MA, USA; Fig. S1).

2.4. Experimental procedure

The OCR of the fish was monitored over 26–27 h. depending on the experimental group (Fig. 1d). To stabilize the water temperature and DO level, the water pump (BT-10, 10 W; Chuangxing Co., Zhongshan, China) and return pump circulated seawater for at least 12 h after the experimental system had been set up. Ten fish were transferred from the stock tanks to the middle chambers and acclimated to the experimental environment for at least 4 h. The experimental groups were: 1) control (no additional noise playback), 2) PD1 (1 h pile driving noise playback followed by one additional playback at the same time the next day), 3) PD2 (24 h pile driving noise playback), and 4) turbine operation noise (TO, 24 h turbine operation noise playback). Each group was tested with two replicates, using two middle chambers (one chamber per replicate), each containing 10 fish. The sample size (n = 10 fish per replicate) was determined based on the experimental design of Chu et al. (2020), which demonstrated sufficient statistical power under comparable conditions. At the end of the experiment (after 26 or 27 h), the fish in each group were anesthetized and blood samples were collected for biochemical analysis.

2.5. Oxygen consumption analysis

Optical sensors (OPTOD, 0–20 mg L⁻¹ measurable range, 0.01 mg L⁻¹ resolution; Aqualabo, Champigny-sur-Marne, France) were installed in the middle of the lids of the upper and lower chambers. The DO concentration and water temperature were recorded every minute during the entire experiment using a module (RTU V2; Dongmoon ENT Co., Seoul, South Korea). OCRs were calculated using the method of Jobling (1982) (Eq. (1)):

$$OCR \left(\mu g \operatorname{O}_2 g^{-1} h^{-1} \right) = \left[\left(C_i - C_f \right) \times F \right] / W$$
(1)

where C_i and C_f are the DO concentration (mg O₂ L⁻¹) before (i.e., upper chamber) and after (i.e., lower chamber) fish respiration, respectively; *F* is the flow rate (L h⁻¹) of the closed circulation chamber system; and *W* is the total wet weight (g) of the fish in the middle chamber. The mean OCR during the first hour of the OCR monitoring period was used to represent the baseline physiological state, and the mean OCR values for each experimental group are shown in Table 1.

2.6. Biochemical analysis: catecholamine and osmolality

The fish were anesthetized for 10 min in 1 L seawater containing 0.3 mL 2-phenoxyethanol (Sigma-Aldrich). To prevent blood clotting, 1-mL syringes with 26-gauge needles were coated with heparin (H3149-10KU; Sigma-Aldrich) prior to blood sample collection. The blood was drawn from the caudal peduncle and centrifuged at 3000 rpm and 4 °C for 10 min using a microcentrifuge (1730R; Labogene, Allerød, Denmark). The supernatant (plasma) was transferred into a 1-mL Eppendorf tube for the catecholamine and osmolality measurements. Catecholamine was measured using a fish catecholamine ELISA kit (MBS015865; MyBiosource, San Diego, CA, USA) and analyzed with a microplate reader (Infinite F Nano+; Tecan, Männedorf, Switzerland). Following the calibration of an osmometer (Osmomat 3000D; Gonotec, Berlin, Germany), 50 µL plasma was used for the osmolality measurement.

2.7. Statistical analysis

The short-term effects of pile driving noise were evaluated in the PD1

Table 1

Mean oxygen consumption rate of test species in each experimental group.

Scientific name (Common name)	Experimental group	Individuals per replicate (n)	Replicates (n)	Experimental time (h)	Total exposure time (h)	Mean OCR (mg $O_2 g^{-1}$ h ⁻¹)
Larimichthys crocea	Control	10	2	27	0	0.224 ± 0.016
(Large yellow croaker)	Pile driving noise 1	10	2	27	2	0.245 ± 0.034
	Pile driving noise 2	10	2	26	24	0.313 ± 0.044
	Turbine operation	10	2	26	24	0.224 ± 0.014
	noise					
Paralichthys olivaceus (Olive flounder)	Control	10	2	27	0	0.111 ± 0.022
	Pile driving noise 1	10	2	27	2	0.122 ± 0.013
	Pile driving noise 2	10	2	26	24	0.106 ± 0.012
	Turbine operation	10	2	26	24	0.112 ± 0.010
	noise					

Abbreviation: OCR, oxygen consumption rate.

group over three 1-h periods before, during, and after exposure. To assess the effects of prolonged noise, data from a 24-h exposure period were compared among experimental groups. Although the control group was not exposed to additional noise, the same periods were evaluated for comparison. The Kruskal–Wallis tests were used to identify differences in OCR across the experimental periods, groups, and photoperiod (McDonald, 2014). The Mann–Whitney *U* test with Bonferroni correction was performed for post-hoc analysis. Differences in the catechol-amine concentration and osmolality were evaluated using Student's *t*-test for two groups and one-way analysis of variance (ANOVA) with Scheffé's post hoc test for three groups (Zar, 2009). The statistical analyses were performed using SPSS 25.0 (IBM Corporation, Armonk, NY, USA; Field, 2013).

3. Results and discussion

3.1. Physiological responses of fish to short-term pile driving noise

Pile driving noise induced stress responses in large yellow croaker (Fig. 2a). In the first trial, the mean OCR was significantly higher during exposure in the PD1 group than it was before exposure in the same group (0.219 vs. 0.195 mg $O_2 g^{-1} h^{-1}$, $H_{5,354} = 201$, p < 0.01) and in the same period in the control group (0.219 vs. 0.211 mg $O_2 g^{-1} h^{-1}$, p < 0.01). The second trial yielded consistent results (0.311 vs. 0.288 mg $O_2 g^{-1} h^{-1}$, $H_{5,354} = 319$, p < 0.01 and 0.311 vs. 0.213 mg $O_2 g^{-1} h^{-1}$, p < 0.01, respectively). In the PD1 group, the OCR did not return to pre-exposure level after exposure in the first trial (0.208 vs. 0.195 mg $O_2 g^{-1} h^{-1}$, $H_{5,354} = 201$, p < 0.01), but it did in the second trial (0.298 and 0.288 mg $O_2 g^{-1} h^{-1}$, $H_{5,354} = 319$, p > 0.7). The catecholamine concentration did not differ between the control and PD1 groups (102 and 121 ng mL⁻¹, t(9) = -1.10, p > 0.3). The osmolality was significantly higher in the PD1 group than in the control group (262 vs. 224 mOsm kg⁻¹, t(16) = 2.43, p < 0.05).

The response of olive flounder to pile driving noise differed from that of large yellow croaker (Fig. 2b). In the first trial, the mean OCR was significantly lower during exposure in the PD1 group than it was before exposure in the same group (0.135 vs. 0.140 mg O₂ g⁻¹ h⁻¹, respectively; $H_{5,354} = 178$, p < 0.01) and in the same period in the control group (0.135 vs. 0.141 mg O₂ g⁻¹ h⁻¹, p < 0.01). The opposite trend was observed in the second trial (0.107 vs. 0.103 mg O₂ g⁻¹ h⁻¹, $H_{5,354} = 329$, p < 0.01 and 0.107 vs. 0.084 mg O₂ g⁻¹ h⁻¹, p < 0.01, respectively). The catecholamine concentration did not differ between the control and PD1 groups (103 and 118 ng mL⁻¹, respectively; t(13) = -0.73, p > 0.4). The osmolality was significantly lower in the PD1 group than in the control group (258 vs. 284 mOsm kg⁻¹, t(16) = -2.59, p < 0.05).

Pile driving noise has been reported to induce acute physiological and behavioral changes in fish, which may recover (Bruintjes et al., 2016a) or habituate (Neo et al., 2015) in the short term. In this study, the stress level of large yellow croaker remained elevated throughout the 1h noise exposure period, suggesting that the physiological impact of noise persists during exposure. Niu et al. (2023) reported that large yellow croaker had strong behavioral responses to pile driving noise at 1530 m, with the peak-to-peak SPL reaching 180.5 dB re 1 μ Pa (~174.5 dB re 1 μ Pa SPL_{z-p}, adjusted by subtracting 6 dB under the assumption of sinusoidal signals). This noise level is comparable to that used in our study, suggesting that farmed fish confined in sea cages, where movement is restricted, would be particularly vulnerable. Consistent with Bruintjes et al. (2016b), interspecific differences in respiration changes according to species-specific sensitivity to sound were observed in this study, highlighting the need for the species-specific investigation of noise effects.

Although the plasma catecholamine concentration was higher in the PD1 group than in the control for both species in this study, the differences were not significant. Cui et al. (2024) reported that the epinephrine level in large vellow croaker was significantly higher than in the control immediately after 1-h exposure to low-frequency (200, 630, and 800 Hz) noise. These findings suggest that noise exposure initially triggers catecholamine secretion, but that its effect diminishes rapidly over time. This pattern could be attributed to the short half-life of catecholamines in fish blood (Rothwell et al., 2005), leading to their degradation during the post-exposure recovery period. As a result, the timing of measurement is critical for the detection of significant differences, as the catecholamine level may already have returned to baseline by the time of sampling. Changes in osmolality showed species-specific responses to noise exposure, with a significant increase in large yellow croaker and a decrease in olive flounder, in this study. Increases in osmolality may be linked to elevated OCRs, as noise-induced stress leads to cortisol secretion (Celi et al., 2016), which enhances Na⁺/K⁺-ATPase activity and ion retention (Laiz-Carrión et al., 2002). In contrast, olive flounder likely employed an energy conservation strategy (Zeng et al., 2019), down-regulating ion transport to reduce osmotic demands and metabolic expenditure. These findings highlight the species-specific nature of osmoregulatory responses to noise stress, and thus the need for tailored assessments of anthropogenic stressors in different fish species.

3.2. Physiological responses of fish to prolonged underwater noise

The temporal variation in the OCR differed depending on the noise source during prolonged (24-h) exposure (Fig. 3a). Under pile driving noise exposure (PD2 group), the OCR of large yellow croaker increased progressively, with more pronounced elevation at night; it peaked at 0.394 mg O₂ g⁻¹ h⁻¹ approximately 11.6 h after playback. By contrast, TO group showed temporal fluctuations similar to those of the control group. During the entire exposure period (1–25 h), the mean OCR in the PD2 group was significantly higher than that in the control group (0.225 vs. 0.316 mg O₂ g⁻¹ h⁻¹, H_{2,4317} = 2761, p < 0.01), with no significant difference from that in the TO group (0.225 and 0.224 mg O₂ g⁻¹ h⁻¹, respectively; p > 0.9). The OCRs of olive flounder in all groups showed a decreasing trend over time. The mean OCR in the PD2 group was



Fig. 2. Oxygen consumption rates (OCRs), catecholamine concentrations, and osmolality in the control and pile driving noise 1 (PD1, short-term exposure) groups for (a) *L. crocea* and (b) *P. olivaceus*. To compare the short-term effects of pile driving noise on OCRs, 1-h means from the pre-, during-, and post-exposure periods in the first and second trials were analyzed.

significantly lower than that in the control group, with no significant difference from that in the TO group (0.113 vs. 0.105 and 0.113 mg O₂ g⁻¹ h⁻¹, *H*_{2,4317} = 306, *p* < 0.01 and *p* > 0.9, respectively). The mean OCRs of large yellow croaker and olive flounder were higher during the dark period (3–17 h) than during the light period (0–3 and 17–26 h; Fig. 3b).

The substantial increases in OCR at night suggest that the impact of noise exposure depends on the diel rhythm of fish. Fish in the Sciaenidae family, commonly known as "drums" or "croakers," were reported to exhibit peak spawning activity and associated vocalizations (viz., drumming) from evening to dawn (Holt et al., 1985; Connaughton and Taylor, 1995). Additionally, the small yellow croaker (*Larimichthys polyactis*, formerly *Pseudosciaena polyactis*) has been reported to show crepuscular and nocturnal feeding activity (Xue et al., 2005). Thus, the prioritization of conservation measures to mitigate the adverse effects of anthropogenic noise for species such as croakers, which depend critically on acoustic signaling for reproduction—an essential determinant of population sustainability—is warranted. Olive flounder, previously documented as a nocturnal species exhibiting high activity levels and elevated OCRs at night (Liu et al., 1997), was more affected by nighttime



Fig. 3. (a–b) Oxygen consumption rates (OCRs), (c) catecholamine concentrations, and (d) osmolality in the control, prolonged pile driving noise (PD2), and turbine operation noise (TO) groups. (b) OCR variations according to the photoperiod, analyzed using means from 10-h light and 14-h dark periods.

noise in this study.

Catecholamine concentrations did not show change significantly in response to underwater noise exposure in either species in this study (Fig. 3c). For large yellow croaker, ANOVA revealed significant differences among experimental groups (control vs. PD2 vs. TO, 102 vs. 105 vs. 67 ng mL⁻¹, $F_{2,15} = 4.82$, p < 0.05), but Scheffé's post hoc test revealed no significant pairwise difference. For olive flounder, no significant difference was found among experimental groups (control, PD2, and TO, 103, 127, and 119 ng mL⁻¹, respectively; $F_{2,26} = 1.20$, p > 0.3). Osmotic responses to noise exposure differed between species (Fig. 3d). In large yellow croaker, the osmolarity was significantly higher in the PD2 group than in the control group, but did not differ significantly between the TO and control groups (control vs. PD2 vs. TO, 224 vs. 271

vs. 260 mOsm kg⁻¹; $F_{2,23} = 5.42$, p < 0.05). In contrast, the osmolarity did not differ significantly among olive flounder groups (control, PD2, and TO, 284, 271, and 288 mOsm kg⁻¹, respectively; $F_{2,24} = 2.52$, p > 0.1). These results suggest that prolonged underwater noise exposure induces species-specific physiological responses, with large yellow croaker displaying greater osmotic sensitivity, potentially due to its reliance on acoustic communication, and olive flounder exhibiting a more stable osmotic profile.

These findings contrast with those of Wang et al. (2025), who reported that exposure to underwater wind turbine noise for 21 consecutive days in a laboratory setting significantly disrupted the feeding, swimming velocity, and growth rate of both large yellow croaker (*L. crocea*) and blackhead seabream (*Acanthopagrus schlegelii*). In their

study, behavioral and physiological indicators showed cumulative stress under continuous noise exposure. In comparison, our results from a 24-h experiment revealed no significant change in oxygen consumption or osmolality under turbine operation noise, suggesting inter-study variation in noise duration, characteristics, and fish holding conditions. These contrasting findings emphasize the importance of exposure duration in shaping physiological responses. They also underscore the need for longterm experiments to evaluate the potential cumulative impacts of operational noise (Popper and Hawkins, 2019).

3.3. Effects of anthropogenic stressors on fish respiratory processes

We reviewed 15 studies in which the effects of stressors from anthropogenic maritime activities on fish respiratory processes (respiration and ventilation) were assessed (Fig. 4 and Table S1). The stressors were underwater noise in 10 studies (Simpson et al., 2015; Simpson et al., 2016; Bruintjes et al., 2016a; Bruintjes et al., 2016b; Debusschere et al., 2016; Nedelec et al., 2016; Radford et al., 2016; Spiga et al., 2017; Harding et al., 2018; Palma et al., 2019), magnetic fields in 3 studies (Formicki, 1992; Perkowski and Formicki, 1997; Jakubowska et al., 2021), and suspended sediment in 2 studies (Hess et al., 2017; Chu et al., 2020). The studies of underwater noise were allocated to impulsive (Fig. 4a) and continuous (Fig. 4b) sound groups, and significant respiratory responses were compared using SPL_{z-p} and SPL_{rms} units, respectively.

Juvenile European seabass (*Dicentrarchus labrax*) showed a decrease in the OCR (viz., respiration rate) when exposed to pile driving noise (SPL_{z-p} of 210 dB re 1 µPa) near a construction site (Debusschere et al., 2016). In playback experiments, the opercular beat rate (OBR; viz., ventilation rate) increased at exposure levels of 200–201 dB re 1 µPa in outdoor setting (Bruintjes et al., 2016a) and >167 dB re 1 µPa in indoor setting (Spiga et al., 2017). For larvae, increases in the ventilation rate were observed at 163 dB re 1 µPa for pile driving noise and 158 dB re 1 µPa for airgun noise in indoor setting (Radford et al., 2016).

Juvenile European eel (*Anguilla anguilla*) showed increases in the respiration rate when exposed to playback of ship noise (SPL_{rms}, 148–149 dB re 1 μ Pa) in outdoor and indoor settings (Simpson et al., 2015). Increases in the ventilation rate were observed at levels

(a) Impulsive sound



(b) Continuous sound

Species	Dev.	Respiratory process		Sound pressure level _{rms} (dB re 1 μ Pa)							
	stage	Ventilation Re	spiration	115 12	20 125	130	135	140	145	150	155
Anguilla anguilla 5 🤍	Juvenile		V	Nois St	se sourc	e				•	
Anguilla anguilla 5 🧹	Juvenile	V	v		lotorboat rilling					A	
Cynotilapia zebroides 6 🐠	Adult		V]				•			
Anguilla anguilla ²	Juvenile	V]							
Hippocampus guttulatus ⁷ 🛝	Adult	V]			•				
Dicentrarchus labrax ³	Juvenile	v]					Se	tting	
Cynotilapia zebroides ⁶	Adult		V		•					Outdoo In situ	or

References ¹ Debusschere et al., 2016; ² Bruintjes et al., 2016a; ³ Spiga et al., 2017; ⁴ Radford et al., 2016; ⁵ Simpson et al., 2015; ⁶ Harding et al., 2018; ⁷ Palma et al., 2019; * *This study*

Fig. 4. Mini-review of the effects of underwater noise on fish respiration across indoor, outdoor, and in situ settings. (a) Impulsive sound sources, including pile driving and seismic airgun noise. (b) Continuous sound sources, including ship, motorboat, and drilling noise. Detailed metadata and additional information on other stressors (magnetic fields and suspended sediments) are provided in Table S1.

exceeding 139–141 dB re 1 μ Pa in indoor setting (Bruintjes et al., 2016a). Adult cichlid (*Cynotilapia zebroides*), a lake-dwelling species, showed increases in the respiration rate when exposed to motorboat noise at 127–142 dB re 1 μ Pa in field setting and to playback at 112–121 dB re 1 μ Pa in outdoor setting (Harding et al., 2018). Analogously, the ventilation rate of adult long-snouted seahorse (*Hippocampus guttulatus*) increased upon exposure to motorboat noise at 112–137 dB re 1 μ Pa in field setting (Palma et al., 2019). Juvenile European seabass (*D. labrax*) had an elevated ventilation rate upon exposure to playback of drilling noise at 132 dB re 1 μ Pa in indoor setting (Spiga et al., 2017).

Taken together, these results demonstrate that increases in OBR serve as a consistent indicator of respiratory stress under noise exposure across diverse taxa. As a non-invasive and relatively simple endpoint, OBR measurements are advantageous in both laboratory and field studies; however, they do not precisely reflect the actual oxygen consumption rate. In contrast, our study employed a quantitative approach using direct OCR measurements, which, although more accurate, required specialized equipment and was constrained by limitations in experimental duration and scale. Accordingly, the selection of physiological endpoints should be tailored to experimental constraints and biological characteristics of the test species, balancing practicality with measurement precision.

All reviewed studies of the effects of magnetic fields and suspended sediments were conducted in indoor settings (Table S1). The respiration rate of rainbow trout (Oncorhynchus mykiss) embryos increased upon exposure to static magnetic fields of 5-300 mT (Perkowski and Formicki, 1997), but did not change in larvae exposed to a 10-mT magnetic field for 40 days (Jakubowska et al., 2021). Larval brown trout (Salmo trutta) had an increased ventilation rate upon exposure to 51-70-mT magnetic fields (Formicki, 1992). In contrast, long-term (40-d) exposure to electromagnetic fields had no significant effect on the respiration rate of larval rainbow trout (O. mykiss; Jakubowska et al., 2021). More recently, Xu et al. (2025) assessed the effects of electromagnetic fields up to 2 mT on large yellow croaker (L. crocea) and blackhead seabream (A. schlegelii), observing significant reductions in opercular movement alongside elevated oxidative stress and immune responses. Collectively, these studies suggest that while freshwater species exhibit variable sensitivity to strong static magnetic fields, even moderate (2 mT) electromagnetic exposure may impair respiratory performance in marine fish, particularly under long-term or cumulative stress conditions. Future studies should therefore consider exposure duration and speciesspecific susceptibility when evaluating electromagnetic impacts.

OWFs generate underwater noise and electromagnetic fields, creating a unique scenario of co-occurring stressors. Noise from pile driving and turbine operation may elevate the metabolic demand and stress level of fish, whereas electromagnetic fields from submarine cables could interfere with their orientational behaviors (Putman et al., 2014; Hutchison et al., 2020). This combined exposure may disrupt migration and foraging, affecting population dynamics (Klimley et al., 2021). With the expansion of offshore infrastructure for renewable energy development, anthropogenic impacts are expected to increase, necessitating a greater focus on their cumulative effects.

Juvenile coral reef fish (*Acanthochromis polyacanthus, Amphiprion melanopus,* and *Amphiprion percula*) showed species-specific sensitivity to suspended sediments at concentrations of 45–180 mg L⁻¹ (Hess et al., 2017). The respiration rate of juvenile olive flounder (*P. olivaceus*) increased upon exposure to sediment concentrations of 1000–4000 mg L⁻¹ (Chu et al., 2020). Coastal development projects, including OWF construction, port expansions, and dredging activities, frequently result in the simultaneous generation of underwater noise and increased suspended sediment levels. Gill function can be impaired by elevated sediment levels, necessitating increased respiratory effort (Sutherland and Meyer, 2007), and noise exposure simultaneously raises the metabolic rate, compounding physiological stress. Moreover, sediment-induced reductions in water clarity may exacerbate behavioral disruptions caused by noise, affecting fish habitat use (Wenger et al., 2011) and

prey-predator interactions (Wenger et al., 2013). As human activity around coastal areas increases, the stressors affecting marine organisms are becoming increasingly diverse and complex. Thus, future research should focus on the evaluation of the combined effects of multiple stressors, rather than individual factors. Environmental impact assessments should also address synergistic interactions among various stressors, such as underwater noise, electromagnetic fields, and suspended sediments, and their cumulative effects on marine life.

4. Conclusion

In this study, the effects of underwater noise generated during OWF construction and operation on the oxygen consumption rate, catecholamine level, and osmolality in fish were evaluated. Short-term pile driving noise elicited species-specific physiological responses in L. crocea and P. olivaceus, while prolonged exposure revealed diel variations in OCRs, with nighttime responses being more pronounced. Continuous turbine operation noise did not induce significant physiological changes in either species. These findings address the research objective by demonstrating that the physiological responses of commercially important marine fishes vary according to noise type. exposure duration, and species-specific traits. We also reviewed the physiological effects of additional anthropogenic stressors including magnetic fields and suspended sediments, to provide broader ecological context. Given the diversity and complexity of stressors associated with offshore developments, future assessments should prioritize investigating cumulative and potentially synergistic effects. To enable effective assessment under field conditions, intensive laboratory-based studies are still required. The findings of this study also provide valuable insights for the addressing of policy issues related to the expansion of renewable energy and social challenges such as public acceptance, both of which are crucial for OWF development and environmental management. As wind energy remains a promising and sustainable energy source, minimizing ecological risks during the construction phase will be critical. Rapid but strategically timed turbine installation alongside consideration of species-specific and diel physiological sensitivity may serve as effective mitigation strategies to reduce physiological stress in fish populations.

CRediT authorship contribution statement

Beomgi Kim: Writing – original draft, Visualization, Formal analysis, Conceptualization. **Gayoung Jin:** Writing – original draft, Visualization, Formal analysis, Conceptualization. **Yujung Byeon:** Formal analysis. **Shin Yeong Park:** Formal analysis. **Hyunseo Song:** Formal analysis. **Changkeun Lee:** Visualization, Project administration, Conceptualization. **Junghyun Lee:** Writing – review & editing, Project administration, Conceptualization. **Junsung Noh:** Writing – review & editing, Visualization, Supervision. **Jong Seong Khim:** Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research was supported by "Development of Advanced Science and Technology for Marine Environmental Impact Assessment (RS-2021-KS211469)" and "Development of marine environmental assessment and monitoring system and fundamental technology for mediumscale demonstration of offshore CCS project (RS-2023-00254680)" of Korea Institute of Marine Science & Technology Promotion (KIMST) funded by the Ministry of Oceans and Fisheries. This work was also supported by the project entitled "Ecosystem functional changes to halophyte and mangrove planting in the coastal wetland: Evaluation of blue carbon storage and food web structure using mesocosm system (RS-2023-00213511)" funded by the National Research Foundation of Korea (NRF) granted to J.N.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2025.118139.

Data availability

Data will be made available on request.

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