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Biological responses to underwater noise in marine ecosystems: A systematic review of taxon-informed threshold ranges[☆]

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ABSTRACT

Anthropogenic underwater noise is an increasingly important stressor in marine ecosystems, yet existing regulatory frameworks remain focused largely on marine mammals. This review synthesized evidence from 130 experimental studies across multiple marine taxa and noise-source categories. Research effort was concentrated on fish (48%) and marine mammals (34%), whereas invertebrates remained underrepresented (13%). Adult life stages dominated the literature, while early life stages accounted for only 6% of observations. Behavioral responses were the most frequently reported endpoint (54%), followed by physiological, hearing, injury/mortality, and developmental effects. Response patterns differed by noise type: continuous noise was more commonly associated with behavioral and physiological responses, whereas impulsive noise was more frequently linked to injury or mortality. Current benchmark systems remain limited for many invertebrates and early life stages. Despite the predominance of laboratory studies, restricted taxonomic coverage, and substantial variability among species and experimental approaches, the available evidence highlights the need for more taxon-resolved exposure standards and reveals critical knowledge gaps for understudied taxa, habitats, and sensitive life stages.

1. Introduction

Underwater noise has emerged as a pervasive anthropogenic stressor in marine environments, driven by the expansion of activities such as commercial shipping, pile driving, dredging, and seismic exploration (Popper and Hawkins, 2019; Byeon et al., 2025). These sources generate both continuous low-frequency noise and impulsive high-intensity sounds that differ in temporal pattern, propagation characteristics, and biological consequences. Intense short-duration sounds may cause acute injury in nearby organisms, whereas lower-level chronic noise can extend across broader spatial scales and interfere with communication, orientation, predator avoidance, feeding, and reproduction (Slabbekoorn et al., 2010; Williams et al., 2015; Kim et al., 2025). Unlike chemical contaminants, acoustic energy can propagate efficiently through seawater over long distances depending on sound frequency and water conditions, creating additional challenges for spatial management (Hawkins and Popper, 2017).

Recent studies further indicate that the effects of underwater noise are not limited to marine mammals (Weilgart, 2018; Rako-Gospić and Picciulin, 2019). For example, offshore wind turbine noise has been shown to induce measurable behavioral and physiological responses in commercially important fishes such as *Larimichthys crocea* and *Acanthopagrus schlegelii* (Wang et al., 2025a). Fish and invertebrates, including taxa lacking specialized auditory organs, also exhibit diverse responses to sound exposure. These responses range from physical injury and endocrine disruption to behavioral alterations (e.g., changes in schooling and feeding) and physiological stress, including oxidative damage and immune suppression (André et al., 2011; Kim et al., 2024; Byeon et al., 2025). Exposure to pile driving noise has likewise been associated with elevated cortisol levels and transcriptional changes in

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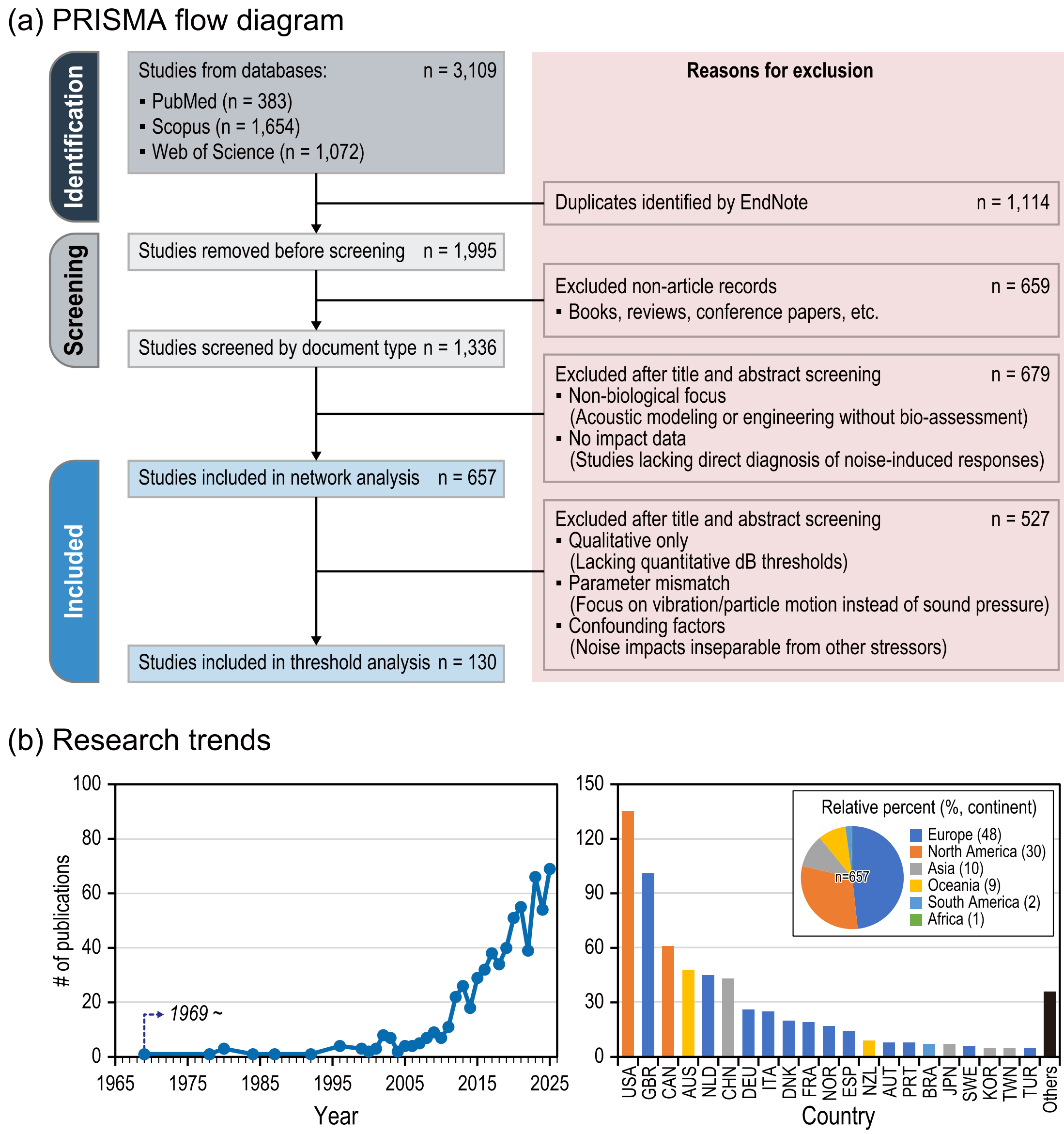

Fig. 1. Study selection process and global research trends in underwater noise studies. (a) PRISMA flow diagram summarizing the screening and exclusion process used in the systematic review, from the initial database search ($n = 3109$) to the final datasets used for keyword network analysis ($n = 657$) and threshold analysis ($n = 130$). (b) Temporal and geographic patterns of publications related to underwater noise.

pathways related to cell regulation and stress responses.

Despite growing evidence, current knowledge remains limited in scope. Laboratory-based experiments dominate the literature and often focus on a narrow group of economically important species (Popper et al., 2014). Early life stages remain underrepresented despite their potentially greater sensitivity to environmental disturbance. Current regulatory guidelines, such as those from the National Oceanic and Atmospheric Administration (NOAA, 2016), also prioritize thresholds for marine mammals, with comparatively few criteria available for fish and invertebrates. More broadly, studies remain unevenly distributed across taxa, habitats, life stages, and noise-source categories, limiting ecological generalization (Popper et al., 2014). In addition, inconsistencies in response metrics and reporting approaches hinder robust cross-study comparisons and threshold synthesis.

While previous syntheses have provided important foundations for understanding underwater noise impacts, they have largely emphasized marine mammals, conceptual frameworks, or selected taxa (Popper et al., 2014; Williams et al., 2015; Hawkins and Popper, 2017). In contrast, the present review provides an updated synthesis focused on broader marine taxa, particularly fishes and invertebrates, and integrates recent experimental evidence to evaluate research biases, biological endpoints, and reported response thresholds. Thus, this study is intended not only to summarize current knowledge, but also to provide a foundation for future taxon-resolved benchmark development and ecosystem-based noise management.

Given the continuing expansion of marine industrial activities, a broader and more integrated understanding of the biological effects of underwater noise is essential. Accordingly, this review aims to: (1) analyze temporal trends in underwater noise impact studies; (2) assess research distributions and biases across noise sources, taxa, life stages, and endpoints; (3) compare biological responses across taxa and noise sources; (4) compile and synthesize reported sound level thresholds by noise source and biological response; and (5) evaluate the relevance and current coverage of available benchmark frameworks. However, the available evidence remains concentrated in a limited number of taxa and habitats. Therefore, the thresholds synthesized here should be interpreted as representative of currently studied groups rather than the full diversity of marine organisms.

2. Materials and methods

2.1. Literature search, screening, and keyword network analysis

To examine research trends in the biological effects of underwater noise on marine organisms, a systematic literature search was conducted using the following search string: ("underwater noise" OR "anthropogenic noise" OR "underwater sound" OR "acoustic disturbance" OR "acoustic pollution" OR "marine noise" OR "radiated noise" OR "ship noise" OR "pile driving" OR "seismic survey") AND ("marine organism" OR "marine species" OR "marine biota" OR "marine fauna" OR "fish" OR "invertebrate" OR "plankton" OR "coral" OR "benthic" OR "marine mammal") AND ("impact" OR "effect" OR "response" OR "behavior" OR "physiology" OR "stress" OR "mortality" OR "hearing loss" OR "masking" OR "reproduction" OR "growth" OR "survival").

Searches were conducted across Web of Science, PubMed, and Scopus. No lower publication-year limit was applied, and all records indexed in each database through December 2025 were considered (PubMed: 1987–2025; Scopus: 1947–2025; Web of Science: 1962–2025). The search yielded 3109 records in total (PubMed, $n = 383$; Scopus, $n = 1654$; Web of Science, $n = 1072$). After removal of 1114 duplicates using EndNote, 1995 records remained for initial screening. Of these, 659 were excluded because they were non-article sources (e.g., books, reviews, conference papers, or other non-original publications). The remaining 1336 studies underwent title and abstract screening, after which 679 records were excluded because they did not address biological responses to underwater noise, focused primarily on engineering or acoustic modelling without biological assessment, or lacked direct evidence of biological effects. Ultimately, 657 experimental studies addressing the biological impacts of underwater noise were retained for keyword network analysis. The screening and selection process is summarized in a PRISMA flow diagram (Fig. 1a).

Keyword network analysis was performed using VOSviewer (version 1.6.10; van Eck and Waltman, Leiden University, The Netherlands) to identify major research themes and co-occurring concepts. The software extracts terms with high co-occurrence frequencies from article titles and abstracts and visualizes their relationships as networks in which node size represents term frequency and link width indicates co-occurrence strength (van Eck and Waltman, 2010; Lee and Khim, 2022). From the underwater noise dataset, 61 keywords occurring more than five times were retained and grouped into five thematic clusters. The top five keywords in each cluster were ranked according to both "Links" and "Total Link Strength" (Stephan et al., 2017) and are presented in Table S1.

2.2. Study selection for threshold analysis

From the 657 studies retained for evidence mapping, a second full-text screening was conducted to identify those suitable for quantitative threshold analysis. Inclusion criteria required controlled experimental studies that: (1) reported underwater noise exposure levels in decibel-based acoustic metrics (e.g., dB re 1 μPa or dB re 1 $\mu Pa^2 \cdot s$), and (2) presented measurable biological responses under clearly defined exposure conditions. Studies were excluded if they: (1) did not provide quantitative threshold values; (2) focused primarily on vibration or particle motion rather than sound pressure; (3) examined non-acoustic stimuli (e.g., visual cues or chemical pollutants); (4) were reviews or simulation-based studies without original experimental data; or (5) reported only ambiguous or indirect biological responses. After applying these criteria, 130 studies were retained for biological research trend evaluation and threshold analysis. This refined dataset enabled systematic comparison of response thresholds across noise sources, taxa, life stages, and endpoint categories (Fig. 1a).

For each selected study, the reported acoustic metrics were recorded together with the corresponding biological thresholds. Root-mean-square sound pressure level (SPLrms, dB re 1 μPa) was most commonly used for continuous sources such as vessel noise, whereas zero-to-peak SPL (SPLz–p, dB re 1 μPa) and sound exposure level (SEL, dB re 1 $\mu Pa^2 \cdot s$) were typically reported for impulsive sources such as pile driving and seismic airgun noise. Threshold data were then organized by noise-source category and acoustic metric for comparative analysis and visualization.

2.3. Classification of study characteristics and trend analysis

To identify overall patterns in experimental studies on underwater noise, the 130 selected articles were classified according to both biological and methodological variables. Acoustic source categories included vessel, sonar/acoustic deterrent device (ADD), pile driving, seismic, and others, with the latter category comprising less frequently reported sources such as playback sounds, equipment noise, vibration, and construction noise. Taxonomic groups were classified as fish, invertebrates, marine mammals, and others, with others including less frequently represented taxa such as birds, rotifers, copepods, and planktonic producers. Life stages were classified as early stage, juvenile, adult, and unknown, whereas biological endpoints were grouped as behavior, physiology, hearing, development, and injury/mortality.

A Sankey diagram was generated in R to visualize interactions among four core variables: (1) noise source, (2) taxonomic group, (3) life stage, and (4) endpoint category. Rather than counting studies alone, each unique experimental setup was treated as an independent observation to better capture the multidimensional structure of experimental designs. Species-level taxonomy was verified using the World Register of Marine Species (WoRMS), FishBase, and SeaLifeBase.

The frequency and distribution of endpoint categories were further examined across taxa to identify research gaps and overrepresented response types. To assess temporal shifts in research focus, the selected studies were additionally compared between pre-2008 (1980–2007) and post-2008 (2008–2025) periods. The year 2008 was selected as a transition point because it coincided with increasing publication activity and the adoption of the European Union Marine Strategy Framework Directive.

2.4. Threshold derivation and comparative synthesis

For each species–endpoint combination, the minimum reported acoustic level associated with a statistically significant biological effect was defined as the lowest observed effect level (LOEL). Statistical significance was accepted according to the criteria used in each original study, as study design, sample size, and analytical framework varied among studies. The highest exposure level showing no significant effect was defined as the no observed effect level (NOEL). Original acoustic metrics reported in each study (e.g., SPLrms for continuous sources and peak-based metrics for impulsive sources) were retained during data extraction to preserve source-specific exposure characteristics.

To facilitate comparison across studies, reported values were reorganized within a common comparative framework and presented by source category while preserving the original metric definitions. However, original metric type and exposure context were explicitly considered during interpretation, and cross-source comparisons were treated cautiously where pulse structure, exposure duration, repetition rate, or cumulative energy differed substantially. For comparative summaries across noise sources, taxonomic groups, life stages, and endpoint categories, LOEL values were used as the primary threshold metric, whereas NOEL values were retained as supporting reference information. Supporting studies used for the synthesized SPLrms comparisons for vessel traffic and pile driving exposures included Erbe (2002), Scholik and Yan (2002), Wysocki et al. (2006), Vasconcelos et al. (2007), Jensen et al. (2009), Buscaino et al. (2010), Hatch et al. (2012), Roberts et al. (2016), Mahanty et al. (2017), Kastelein et al. (2019), Mickle et al. (2019), Palma et al. (2019), Wale et al. (2019), Alves et al. (2021), Vieira et al. (2021), Fleissner et al. (2022), van der Knaap et al. (2022), Niu et al.

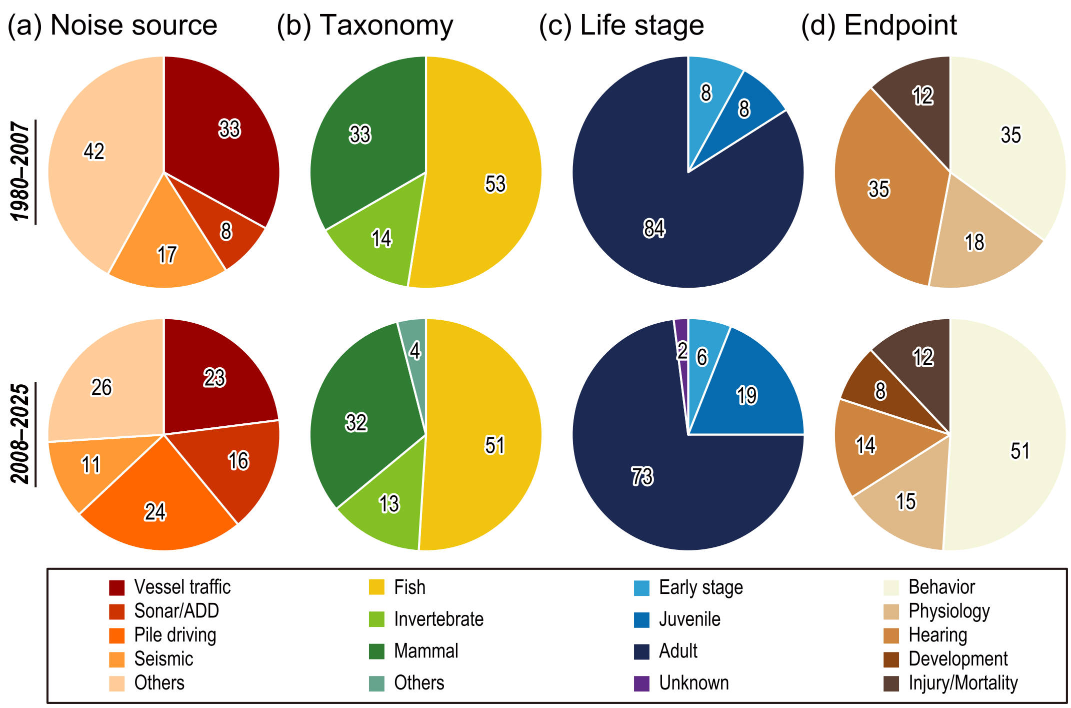

Fig. 2. Temporal comparison of research patterns in underwater noise studies between (a) 1980–2007 (pre-2008) and (b) 2008–2025 (post-2008). Pie charts show the proportional distribution of studies by noise source, taxonomic group, life stage, and endpoint category for each period, highlighting shifts in research focus over time.

(2023), Rojas et al. (2023), Solé et al. (2023), Badlowski and Boyle (2024), Taylor et al. (2024), Tennessen et al. (2024), Diamant et al. (2025), Hermannsen et al. (2025), Jézéquel et al. (2025), Kim et al. (2025), Pan et al. (2025), Vergara et al. (2025), Wang et al. (2025b), and Xu et al. (2025). The resulting threshold dataset was then stratified by taxonomic group (fish, invertebrates, marine mammals, and other marine taxa), life stage (early stage, juvenile, and adult), and endpoint category (behavior, physiology, hearing, development, and injury/mortality). Where multiple thresholds were reported under the same condition, the lowest value was retained as a conservative reference. This dataset formed the basis for evaluating intergroup sensitivity differences and identifying taxa or traits potentially associated with heightened vulnerability to underwater noise exposure.

2.5. Benchmark comparison with existing criteria

From the dataset compiled in Section 2.4, LOEL values were selected as representative thresholds for each taxonomic group. These thresholds were then compared with established benchmark criteria proposed by Popper et al. (2014) and NOAA (2024), which provide exposure guidance for fish and marine mammals, respectively. Comparisons included SPL metrics (SPLrms and SPLz-p), as well as SEL, where available. Thresholds were organized by noise-source category and acoustic metric to enable direct side-by-side comparison with existing benchmark frameworks.

3. Results and discussion

3.1. Global research trends on underwater noise

Experimental studies on the biological effects of underwater noise remained limited until the 1990s, but publication output increased gradually in the early 2000s and rose sharply after 2010 (Fig. 1b). This trend broadly coincided with the expansion of marine industries such as commercial shipping, offshore energy, and dredging, together with growing scientific and regulatory attention to underwater noise. In terms of geographic distribution, research efforts were unevenly distributed across regions. Europe accounted for 48% of publications, followed by North America (30%) and Asia (10%). At the country level, the United States had the highest share (21%), followed by the United Kingdom (16%), Canada (9%), Australia (7%), the Netherlands (7%), China (7%), and other countries each contributing less than 5%. The strong European representation likely reflects early regulatory attention to underwater noise together with rapid offshore energy development in European waters. This distribution, however, does not fully reflect the current offshore wind market, an increasingly important source of anthropogenic underwater noise. According to the Global Wind Energy Council (2025), China accounts for 50% of total offshore wind installations, followed by the United Kingdom (19%), Germany (11%), the Netherlands (6%), Denmark (3%), and other countries collectively accounting for 11%. This mismatch highlights an important geographic knowledge gap, as several rapidly expanding marine industrial regions remain underrepresented in the literature. Addressing this imbalance should be a priority for future underwater noise research.

To further characterize research themes, a keyword co-occurrence analysis was conducted based on 657 experimental studies. The 61 most frequent keywords (≥5 occurrences) were grouped into five thematic clusters, each representing a distinct research domain (Fig. S1a and Table S1). Group 1 highlighted anthropogenic sources such as pile driving and offshore wind farms, particularly in relation to noise pollution and stress responses. Group 2 focused on fish, masking effects, and physiological endpoints. Group 3 centered on marine mammals and invertebrates, often linked to seismic surveys and renewable energy. Group 4 reflected research on habituation and stress in estuarine and commercially important species such as *Dicentrarchus labrax*. Group 5 captured passive acoustic monitoring and species identification, with keywords such as "humpback whale" and "automatic identification system" reflecting advances in acoustic tracking technologies. Temporal analysis of keyword trends revealed a notable shift in research priorities (Fig. S1b). Earlier studies (pre-2015) primarily addressed stress and behavioral responses to major noise sources. In contrast, post-2015 research increasingly incorporated cumulative impacts, habitat-

		Noise source	Vessel traffic					Sonar/ADD					Pile driving					Seismic					Others				
Taxonomy	Phylum	Class / Endpoint	B	P	H	D	I	B	P	H	D	I	B	P	H	D	I	B	P	H	D	I	B	P	H	D	I
Fish	Chordata	Actinopterygii	33	11	8	1	3	1					16	2	5		10	21				2	30	28	14	13	9
		Chondrichthyes																4									
Invertebrate	Arthropoda	Malacostraca	1				1						1				1				2			2		1	
		Merostomata																					1	1			1
	Cnidaria	Anthozoa					2										2										
	Mollusca	Bivalvia	1	1					6				1			1							4	3	1	1	
		Cephalopoda										2	8		1		1						2				1
Mammal	Chordata	Mammalia	30		3			36	4	3			24	1	2			20	2	1			5	1	2		
Others	Arthropoda	Hexanauplia																			1	1					
	Bacillariophyta	Bacillariophyceae												1		4											
	Chlorophyta	Chlorophyceae												1		4											
	Chordata	Aves						1																			
	Haptophyta	Prymnesiophyceae												1		4											
# of publications			*30*	*6*	*9*	*1*	*3*	*18*	*5*	*3*		*2*	*22*	*3*	*7*	*2*	*7*	*14*	*1*	*1*	*2*	*2*	*23*	*17*	*11*	*9*	*10*

Endpoint B: Behavior, P: Physiology, H: Hearing, D: Development, I: Injury/Mortality # of observations 1–2 3–5 6–10 11–20 > 20

Fig. 3. Distribution of reported biological endpoints across taxonomic groups and underwater noise sources. Rows represent major taxonomic categories and lower-level classifications, whereas columns indicate noise-source types (vessel, sonar/ADD, pile driving, seismic, others) and endpoint categories (behavior, physiology, hearing, development, injury/mortality). Colored cells indicate the number of observations for each combination, and the bottom row summarizes publication counts by noise source and endpoint category.

specific considerations, and non-mammalian taxa, indicating a shift toward more ecosystem-oriented and taxonomically inclusive approaches.

3.2. Trends in experimental studies on underwater noise

Temporal comparisons and category frequencies revealed clear shifts in research priorities across the 130 eligible studies (Fig. 2 and Fig. S2). Before 2008, vessel traffic was the dominant source category, whereas after 2008 the contribution of pile driving increased to 24%, and that of sonar/ADD to 16%, consistent with growing research attention to expanding offshore industrial activities. Fish and marine mammals remained the most frequently studied taxa overall (48% and 34%, respectively), while invertebrates accounted for only 13% of records. The predominance of fish likely reflects their ecological and commercial importance, together with their well-documented auditory sensitivity to underwater noise (Scholik and Yan, 2001). Invertebrates, by contrast, remained comparatively underrepresented despite their ecological significance. Adult stages remained dominant (71%), whereas juveniles (20%) and early stages (6%) remained comparatively scarce. These patterns indicate that although study scope has diversified over time, the current evidence base remains concentrated on vertebrate taxa and mature life stages, limiting broader ecological inference across marine communities (Hawkins and Popper, 2017).

Behavioral responses were the most frequently assessed endpoint across the full study period, accounting for 54% of all observations and substantially exceeding physiological (16%), hearing (13%), injury/mortality (11%), and developmental responses (6%) (Fig. S2). Their predominance likely reflects the fact that behavioral changes are non-lethal, rapidly detectable, and readily quantified under experimental conditions. Before 2008, studies focused largely on vessel-noise effects in adult fish and marine mammals, whereas post-2008 studies increasingly incorporated additional source types, juvenile stages, and broader endpoint categories (Fig. 2). This shift suggests a transition from relatively narrow source-specific disturbance studies toward more integrative assessments that consider multiple exposure scenarios and sublethal biological responses. Nevertheless, the continued dominance of behavioral endpoints indicates that longer-term consequences related to growth, reproduction, and fitness remain insufficiently resolved (Hawkins and Popper, 2017; Blom et al., 2019).

Research coverage also varied substantially among noise sources and taxonomic groups (Fig. S3). Across most source categories, fish and marine mammals showed both higher study counts and greater species richness than invertebrates. The limited representation of invertebrates may reflect their high taxonomic diversity, incomplete understanding of sensory mechanisms, and the lack of standardized protocols for noise-response testing. Several categories also showed a high mean number of studies per species, indicating repeated reliance on a limited number of model or priority species. Frequently tested taxa included *Phocoena phocoena* and *Tursiops truncatus* in sonar/ADD studies, *Gadus morhua* in seismic studies, and *Poecilia reticulata* in pile driving studies. Repeated use of model species can improve cross-study comparability but may simultaneously bias synthesized thresholds toward a narrow subset of well-studied organisms. This concern is particularly important when repeatedly tested species possess atypical hearing capabilities that may not represent broader taxonomic sensitivity. By identifying these taxonomic concentrations, the present review highlights priority groups requiring broader future testing to improve benchmark representativeness (Popper and Hawkins, 2019; Sasaki et al., 2025).

Several biological and methodological factors likely contribute to the observed research biases and threshold variability among taxa, life stages, and noise-source categories. Sensory anatomy is an important driver, as fishes possessing swim bladders or specialized hearing structures often respond differently to sound pressure than chondrichthyans and many invertebrates, which rely more strongly on particle motion (Popper and Hawkins, 2019). Early life stages are often more vulnerable because eggs and larvae possess developing sensory systems, limited mobility, and reduced avoidance capacity (de Soto et al., 2013). Consequently, the current underrepresentation of early life stages can constrain evaluation of population-level processes such as recruitment, settlement, and early survival. Threshold differences may also depend on whether exposures are acute, repeated, or chronic, as cumulative stress can alter response magnitude and recovery potential. Moreover, variation in acoustic metrics, exposure design, and laboratory conditions can confound comparisons by reflecting methodological inconsistency rather than biological sensitivity alone. The predominance of laboratory studies may further limit ecological realism because natural soundscapes include fluctuating background noise, habitat complexity,

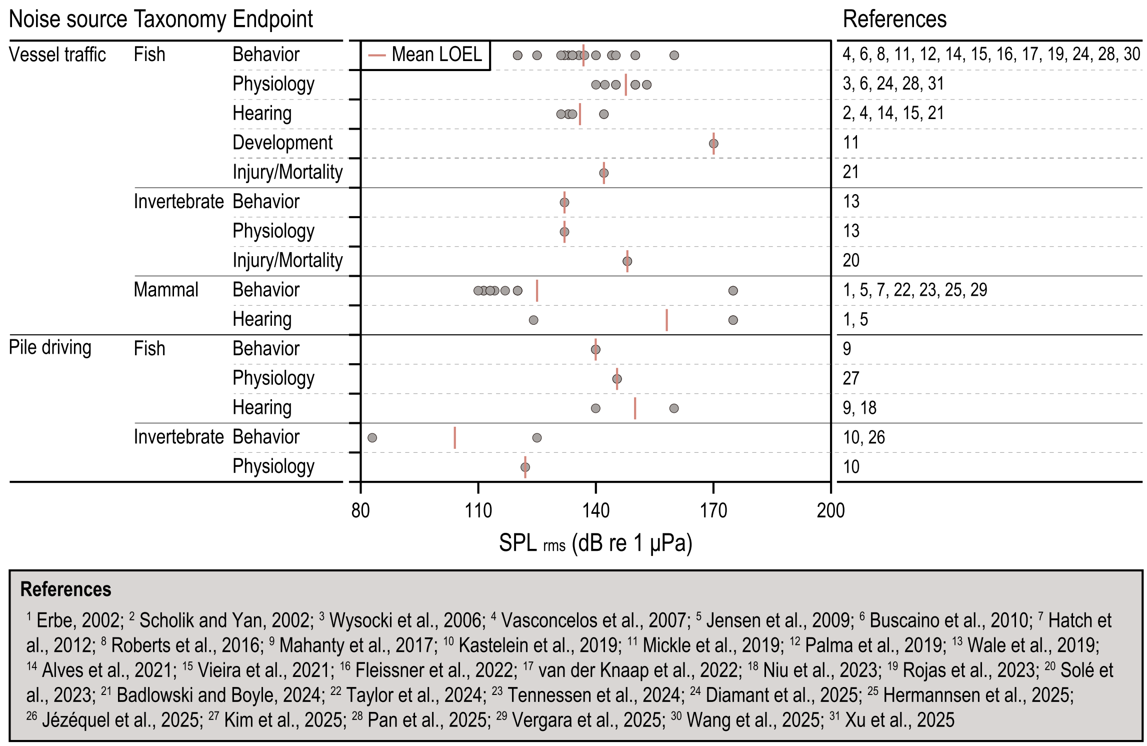

Fig. 4. Synthesized sound pressure levels associated with reported biological responses to major anthropogenic noise sources (vessel traffic and pile driving) across taxonomic groups. Response ranges are shown by taxonomic category and endpoint type (behavior, physiology, hearing, development, injury/mortality). Individual points indicate reported effect levels from experimental studies, horizontal bars indicate the reported range within each category, and vertical ticks indicate the mean LOEL values. All values are presented on a common dB re 1 μPa basis for comparison. Reference numbers correspond to studies listed below the figure.

and repeated multi-stressor exposure. These gaps suggest that future benchmark frameworks should incorporate broader taxonomic coverage and life stage sensitivity rather than relying primarily on adult vertebrate data.

3.3. Patterns of biological responses by taxon and noise source

Reported biological responses varied substantially among taxa and noise-source categories (Fig. 3). Fish represented the largest number of observations in vessel traffic (56 records), pile driving (33), seismic (27), and other noise categories (94), whereas marine mammals were most prominent in sonar/ADD studies (43). Invertebrates were comparatively underrepresented overall, with their greatest contribution occurring under pile driving. These rankings indicate that detailed response evidence remains concentrated on vertebrate taxa, particularly fish and marine mammals.

Response composition differed markedly by source type. Behavioral responses ranked first in every noise-source category, with approximately 65 records for vessel traffic, 38 for sonar/ADD, 50 for pile driving, 45 for seismic, and 42 for other noise sources. The predominance of behavioral endpoints under vessel traffic and sonar/ADD likely reflects the practical ease of observing movement, avoidance, and disturbance responses, together with longstanding management concern over habitat displacement in mobile vertebrates. The next most prominent endpoint differed among sources. Physiological responses were relatively prominent in other noise categories, hearing responses were notable in vessel traffic and pile driving, and injury/mortality records were highest under pile driving. By contrast, the wider distribution of hearing, developmental, and injury-related endpoints under pile driving is consistent with the impulsive, high-intensity nature of construction noise. This pattern reflects the risks of acute trauma and sublethal sensory or developmental effects (Popper et al., 2014; Hawkins and Popper, 2017).

Differences between publication frequency (Fig. 2) and total response observations (Fig. 3) indicate that study counts alone do not capture research depth. For example, pile driving represented 23% of eligible studies (Fig. 2) yet generated one of the most diverse endpoint profiles in Fig. 3, whereas sonar/ADD accounted for 16% of studies but remained concentrated largely on marine mammals and behavioral responses. Likewise, other noise sources showed comparatively broad response coverage, especially in fishes, despite being grouped outside the four main source classes. These contrasts suggest that some categories have been examined through multi-endpoint experimental designs, whereas others have been repeatedly assessed using narrower response frameworks. By integrating publication frequency with response-level observations, the present review distinguishes areas supported by extensive and endpoint-diverse evidence. It also identifies categories where important taxonomic or mechanistic gaps remain.

3.4. Threshold patterns and comparison with international criteria

Synthesized LOEL values varied widely among source categories, with the clearest contrast occurring between continuous and impulsive noise sources (Fig. 4 and Fig. S4; Table S2–S6). Under continuous exposures, relatively low thresholds were reported for vessel traffic and miscellaneous operational sounds. Under vessel traffic, behavioral responses began at 109.9 dB re 1 μPa in marine mammals, 120 dB re 1 μPa in fish, and fish hearing responses at 131 dB re 1 μPa. In the "other noise" category, fish physiological responses were reported from 80 dB re 1 μPa, while invertebrate developmental responses began at 90 dB re 1 μPa. By contrast, pile driving fish responses under SPLrms generally began near 140 dB re 1 μPa, and seismic fish responses under peak-based metrics were typically reported from 195 dB re 1 μPa or higher. These patterns suggest that continuous noise more often induces lower-level behavioral or physiological disturbance, whereas impulsive sounds are associated with stronger instantaneous exposures (Erbe et al., 2019;

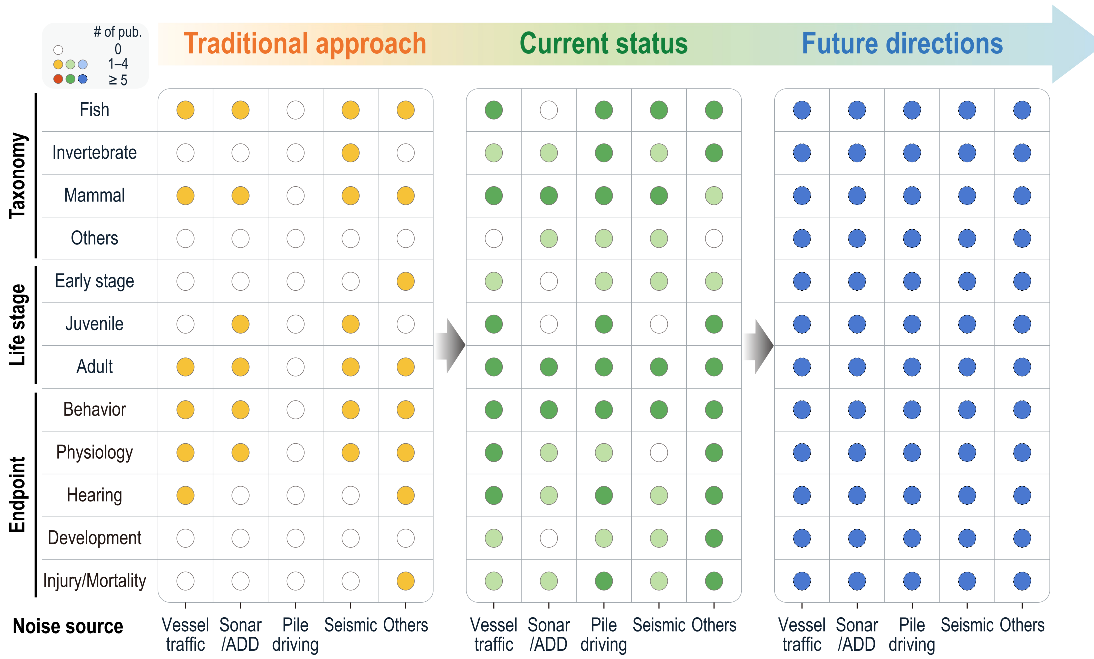

Fig. 5. Conceptual framework illustrating the evolution of underwater noise research from traditional approaches to current understanding and future directions. Circle colors indicate the number of publications within each research dimension (noise source, taxonomy, life stage, and endpoint), showing shifts in evidence coverage over time. The future framework emphasizes key priorities for upcoming studies, including broader taxonomic and life stage representation, multi-source exposure scenarios, fitness- and development-related endpoints, and stronger integration across research dimensions through interconnected study designs.

Hawkins and Popper, 2017).

A second notable pattern emerged across endpoint categories. Under continuous sources, lower LOELs were most often associated with behavioral or physiological responses, whereas higher thresholds under pile driving and seismic exposure were more frequently linked to hearing, injury, or other acute responses. For vessel traffic, fish behavioral effects were observed from 120 dB re 1 μPa, whereas developmental and injury endpoints were scarce. In pile driving studies, hearing and injury-related responses were reported from approximately 140–167 dB re 1 μPa, with some invertebrate responses reaching 195 dB re 1 μPa. This contrast is consistent with chronic noise affecting movement or stress pathways, whereas impulsive noise more often raises concern over sensory damage or barotrauma (Popper et al., 2014; Southall et al., 2021).

Taxonomic comparisons also revealed meaningful differences. Marine mammals frequently showed lower LOELs than fish under continuous noise, with behavioral responses beginning at 98 dB re 1 μPa for sonar/ADD and 109.9 dB re 1 μPa for vessel traffic. This likely reflects their strong dependence on acoustic communication, navigation, and prey detection. Fish exhibited the widest range of endpoints, spanning behavior, physiology, hearing, development, and injury categories, reflecting both higher study numbers and substantial interspecific variability. Although invertebrates were represented by fewer studies, available thresholds often overlapped vertebrate ranges, including responses in cephalopods at 83 dB re 1 μPa, developmental effects in crustaceans at 90 dB re 1 μPa, and physiological responses in bivalves at 120–145 dB re 1 μPa. These findings suggest that limited invertebrate evidence should be interpreted as a data gap rather than low sensitivity, particularly because several invertebrate groups, planktonic taxa, and other understudied marine organisms remain poorly represented in the current evidence base. This limitation should be considered when interpreting synthesized benchmark values (de Soto et al., 2013; Popper and Hawkins, 2019).

Direct comparisons among sources should nevertheless be interpreted cautiously. Although values were reorganized into a common SPL-based framework to facilitate comparison (Fig. 4; Fig. S4), original studies differed in pulse structure, exposure duration, repetition rate, cumulative energy, and measured biological endpoints. Accordingly, the most robust conclusion from the present synthesis is comparative rather than prescriptive: continuous noise sources tend to elicit lower-threshold chronic responses, whereas impulsive sources more often generate higher-threshold acute effects (Erbe et al., 2019; Duarte et al., 2021).

3.5. *Existing benchmark frameworks: gaps and future priorities*

Existing underwater-noise benchmark frameworks remain largely focused on vertebrate taxa, particularly marine mammals and fishes, with limited coverage for other marine groups (Table S7). NOAA guidance provides comprehensive criteria for marine mammals, including non-impulsive SPLrms thresholds of 181–201 dB re 1 μPa for cetaceans and 195–199 dB re 1 μPa for pinnipeds (NOAA, 2024), while Popper et al. (2014) proposed fish criteria of 158 dB re 1 μPa SPLrms for non-impulsive exposure and 186 dB re 1 $\mu Pa^2 \cdot s$ SEL (TTS) for impulsive exposure. In comparison, synthesized LOELs in the present review were often lower, with non-impulsive mammal responses at 98–192 dB re 1 μPa, fish responses at 80–170 dB re 1 μPa, and impulsive fish responses at 139–217 dB re 1 $\mu Pa^2 \cdot s$ SEL. This suggests that current benchmarks mainly target auditory injury, whereas many reviewed studies reported earlier behavioral or physiological responses (Southall et al., 2021; Erbe et al., 2019).

A key finding was the absence of formal criteria for invertebrates despite measurable responses across multiple source types (Table S7). Invertebrate LOELs ranged from 90 to 150 dB re 1 μPa under non-impulsive noise and from 83 to 195 dB re 1 μPa SPLrms or 170 dB re 1 $\mu Pa^2 \cdot s$ SEL. These values indicate a major evidence gap rather than low sensitivity. Repeated sublethal disturbances may accumulate over time and affect growth, reproduction, recruitment, and ecosystem functioning. Because the present synthesis was based largely on sound-pressure metrics, thresholds for taxa relying primarily on particle motion should be interpreted cautiously. Future benchmark development should therefore expand taxonomic coverage, include early life stages, and integrate particle-motion and chronic ecological responses alongside acute injury thresholds.

Consistent with these patterns, underwater-noise research is shifting from traditional source-specific and vertebrate-dominated approaches toward broader ecosystem-based assessment frameworks (Fig. 5). Earlier studies were largely concentrated on vessel traffic and other continuous sources, adult fishes and marine mammals, and injury-oriented thresholds, whereas the current evidence base has expanded to include pile driving noise, increasing invertebrate representation, and behavioral endpoints. Building on this transition, future priorities should emphasize multi-source exposure scenarios, broader taxonomic coverage, early life stages, fitness-related endpoints, and integrated benchmark systems that account for both sound-pressure and particle-motion pathways. Such advances would improve the ecological relevance and management applicability of next-generation underwater-noise criteria (Popper and Hawkins, 2019; Duarte et al., 2021).

4. Conclusions

Biological responses to underwater noise vary substantially across taxa, life stages, and exposure contexts, indicating that uniform threshold approaches are unlikely to provide consistent protection across marine ecosystems. Current benchmark systems remain unevenly developed, with the strongest coverage for marine mammals and more limited criteria for many fish, invertebrates, and early life stages. Future progress will depend on broader taxonomic inclusion, greater attention to sensitive life stages, standardized cumulative exposure metrics such as SEL, and integration of sublethal responses alongside injury-based thresholds. Incorporating particle-motion measures where relevant will further strengthen next-generation frameworks. Overall, more inclusive and ecosystem-oriented criteria are needed to manage the continuing expansion of anthropogenic underwater noise in marine environments.

CRediT authorship contribution statement

Shin Yeong Park: Writing – original draft, Visualization, Formal analysis, Data curation. **Yujung Byeon:** Writing – original draft, Formal analysis, Data curation, Conceptualization. **Junghyun Lee:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Data curation, Conceptualization. **Beomgi Kim:** Formal analysis, Data curation. **Jong Seong Khim:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Funding acquisition.

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.

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Appendix A. Supplementary data

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References

Alves, D., Vieira, M., Amorim, M.C.P., Fonseca, P.J., 2021. Boat noise interferes with Lusitanian toadfish acoustic communication. J. Exp. Biol. 224 (11), jeb234849.
André, M., Solé, M., Lenoir, M., Durfort, M., Quero, C., Mas, A., Lombarte, A., van der Schaar, M., López-Bejar, M., Morell, M., Zaugg, S., Houégnigan, L., 2011. Low-frequency sounds induce acoustic trauma in cephalopods. Front. Ecol. Environ. 9 (9), 489–493.
Badlowski, G.A., Boyle, K.S., 2024. Repeated boat noise exposure damages inner ear sensory hair cells and decreases hearing sensitivity in Atlantic croaker (*Micropogonias undulatus*). J. Exp. Biol. 227 (2), jeb245093.
Blom, E.L., Kvarnemo, C., Dekhla, I., Schöld, S., Andersson, M.H., Svensson, O., Amorim, M.C.P., 2019. Continuous but not intermittent noise has a negative impact on mating success in a marine fish with paternal care. Sci. Rep. 9 (1), 5494.
Buscaino, G., Filiciotto, F., Buffa, G., Bellante, A., Di Stefano, V., Assenza, A., Fazio, F., Caola, G., Mazzola, S., 2010. Impact of an acoustic stimulus on the motility and blood parameters of European sea bass (*Dicentrarchus labrax* L.) and gilthead sea bream (*Sparus aurata* L.). Mar. Environ. Res. 69 (3), 136–142.
Byeon, Y., Lee, J., Kim, B., Hong, S., Khim, J.S., 2025. Evaluation of morphological and physiological effects of pile driving noise on marine microalgae using flow cytometry and pulse-amplitude modulated fluorometry. Mar. Pollut. Bull. 218, 118226.
Diamant, R., Cohen, E., Shachar, I., Kipnis, D., Mišković, N., Zemah-Shamir, Z., Itay, P., Morick, D., 2025. A data-driven approach to compare behavioral and physiological metrics of gilthead sea bream exposed to playback ship noise to a control group. Ecol. Inform. 92, 103491.
Duarte, C.M., Chapuis, L., Collin, S.P., Costa, D.P., Devassy, R.P., Eguiluz, V.M., Erbe, C., Gordon, T.A.C., Halpern, B.S., Harding, H.R., Havlik, M.N., Meekan, M., Merchant, N.D., Miksis-Olds, J.L., Parsons, M., Predragovic, M., Radford, A.N., Radford, C.A., Simpson, S.D., Slabbekoorn, H., Staaterman, E., Van Opzeeland, I., Winderen, J., Juanes, F., 2021. The soundscape of the Anthropocene ocean. Science 371 (6529), eaba4658.
van Eck, N.J., Waltman, L., 2010. Software survey: VOSviewer, a computer program for bibliometric mapping. Scientometrics 84, 523–538.
Erbe, C., 2002. Underwater noise of whale-watching boats and potential effects on killer whales (*Orcinus orca*), based on an acoustic impact model. Marine Mammal Sci. 18 (2), 394–418.
Erbe, C., Marley, S.A., Schoeman, R.P., Smith, J.N., Trigg, L.E., Embling, C.B., 2019. The effects of ship noise on marine mammals: A review. Front. Mar. Sci. 6, 606.
Fleissner, E.R., Putland, R.L., Mensinger, A.F., 2022. The effect of boat sound on freshwater fish behavior in public (motorized) and wilderness (nonmotorized) lakes. Environ. Biol. Fish 105 (8), 1065–1079.
Global Wind Energy Council (GWEC), 2025. Global Offshore Wind Report 2025. GWEC Market Intelligence. June 2025. Available at: https://gwec.net.
Hatch, L.T., Clark, C.W., Van Parijs, S.M., Frankel, A.S., Ponirakis, D.W., 2012. Quantifying loss of acoustic communication space for right whales in and around a US National Marine Sanctuary. Conserv. Biol. 26 (6), 983–994.
Hawkins, A.D., Popper, A.N., 2017. A sound approach to assessing the impact of underwater noise on marine fishes and invertebrates. ICES J. Mar. Sci. 74 (3), 635–651.
Hermannsen, L., Ladegaard, M., Tønnesen, P., Malinka, C., Beedholm, K., Tougaard, J., Rojano-Doñate, L., Tyack, P.L., Madsen, P.T., 2025. High-frequency vessel noise can mask porpoise echolocation. J. Exp. Biol. 228 (6), jeb249963.
Jensen, F.H., Bejder, L., Wahlberg, M., Soto, N.A., Johnson, M., Madsen, P.T., 2009. Vessel noise effects on delphinid communication. Mar. Ecol. Prog. Ser. 395, 161–175.
Jézéquel, Y., Jandial, P., Cones, S.F., Ferguson, S., Aoki, N., Girdhar, Y., Mooney, T.A., 2025. Short-term habituation of the longfin squid (*Doryteuthis pealeii*) to pile driving sound. ICES J. Mar. Sci. 82 (3), fsad157.
Kastelein, R.A., Huijser, L.A., Cornelisse, S., Helder-Hoek, L., Jennings, N., de Jong, C.A., 2019. Effect of pile-driving playback sound level on fish-catching efficiency in harbor porpoises (*Phocoena phocoena*). Aquat. Mamm. 45 (4), 398–410.
Kim, B., Jin, G., Byeon, Y., Park, S.Y., Lee, C., Lee, J., Noh, J., Khim, J.S., 2024. Pile driving noise impacts behavioral patterns of important East Asian juvenile marine fishes. Mar. Pollut. Bull. 207, 116893.
Kim, B., Jin, G., Byeon, Y., Park, S.Y., Song, H., Lee, C., Lee, J., Noh, J., Khim, J.S., 2025. Monitoring of the physiological responses of marine fishes to construction and operation noise from offshore wind farms. Mar. Pollut. Bull. 218, 118139.
van der Knaap, I., Ashe, E., Hannay, D., Bergman, A.G., Nielsen, K.A., Lo, C.F., Williams, R., 2022. Behavioural responses of wild Pacific salmon and herring to boat noise. Mar. Pollut. Bull. 174, 113257.
Lee, J., Khim, J.S., 2022. Revisited a sediment quality triad approach in the Korean coastal waters: Past research, current status, and future directions. Environ. Pollut. 292, 118262.
Mahanty, M. Mohan, Latha, G., Sanjana, M.C., Thirunavukarasu, A., 2017. Passive acoustic observations in the shallow waters of Northwest Bay of Bengal to study the effects of impact pile driving on fish chorus. Mar. Technol. Soc. J. 51 (1), 23–31.
Mickle, M.F., Harris, C.M., Love, O.P., Higgs, D.M., 2019. Behavioural and morphological changes in fish exposed to ecologically relevant boat noises. Can. J. Fish. Aquat. Sci. 76 (10), 1845–1853.
Niu, F., Xie, J., Zhang, X., Xue, R., Chen, B., Liu, Z., Yang, Y., 2023. Assessing differences in acoustic characteristics from impact and vibratory pile installation and their potential effects on the large yellow croaker (*Pseudosciaena crocea*). Front. Mar. Sci. 10, 1106980.
NOAA, 2016. Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing: Underwater Acoustic Thresholds for Onset of Permanent

and Temporary Threshold Shifts. U.S. Department of Commerce. NOAA Technical Memorandum NMFS-OPR-55.

NOAA, 2024. Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Version 3.0): Underwater and In-air Criteria for Onset of Auditory Injury and Temporary Threshold Shifts. U.S. Department of Commerce. NOAA Technical Memorandum NMFS-OPR-71 October 2024.

Palma, J., Magalhães, M., Correia, M., Andrade, J.P., 2019. Effects of anthropogenic noise as a source of acoustic stress in wild populations of *Hippocampus guttulatus* in the Ria Formosa, south Portugal. Aquat. Conserv.: Mar. Freshw. Ecosyst. 29 (5), 751–759.

Pan, Y., Gao, Y., Shi, Y., Xu, J., Fan, H., Khan, F.U., Wang, Y., Zheng, Y., Hu, M., 2025. Underwater noise impairs the health of juvenile hybrid sturgeon based on blood parameters. Aquat. Ecol. 59 (2), 725–740.

Popper, A.N., Hawkins, A.D., 2019. An overview of fish bioacoustics and the impacts of anthropogenic sounds on fishes. J. Fish Biol. 94, 692–713.

Popper, A.N., Hawkins, A.D., Fay, R.R., Mann, D.A., Bartol, S., Carlson, T.J., Coombs, S., Ellison, W.T., Gentry, R.L., Halvorsen, M.B., Løkkeborg, S., Rogers, P.H., Southall, B. L., Zeddies, D.G., Tavolga, W.N., 2014. Sound exposure guidelines for fishes and sea turtles: A technical report prepared by ANSI-Accredited Standards Committee S3/SC1 and registered with ANSI. Springer, Cham, pp. 33–51.

Rako-Gospić, N., Picciulin, M., 2019. Underwater noise: Sources and effects on marine life. In: World seas: an environmental evaluation. Academic Press, pp. 367–389.

Roberts, L., Pérez-Domínguez, R., Elliott, M., 2016. Use of baited remote underwater video (BRUV) and motion analysis for studying the impacts of underwater noise upon free ranging fish and implications for marine energy management. Mar. Pollut. Bull. 112 (1–2), 75–85.

Rojas, E., Prosnier, L., Pradeau, A., Boyer, N., Médoc, V., 2023. Anthropogenic noise does not strengthen multiple-predator effects in a freshwater invasive fish. J. Fish Biol. 102 (6), 1470–1480.

Sasaki, M., Isanta-Navarro, J., Govaert, L., 2025. Experimental ecology and the balance between realism and feasibility in aquatic ecosystems. Nat. Commun. 16 (1), 5142.

Scholik, A.R., Yan, H.Y., 2001. Effects of underwater noise on auditory sensitivity of a cyprinid fish. Hear. Res. 152 (1–2), 17–24.

Scholik, A.R., Yan, H.Y., 2002. Effects of boat engine noise on the auditory sensitivity of the fathead minnow, *Pimephales promelas*. Environ. Biol. Fish 63 (2), 203–209.

Slabbekoorn, H., Bouton, N., van Opzeeland, I., Coers, A., ten Cate, C., Popper, A.N., 2010. A noisy spring: the impact of globally rising underwater sound levels on fish. Trends Ecol. Evol. 25 (7), 419–427.

Solé, M., De Vreese, S., Fortuno, J.M., Van der Schaar, M., 2023. Artificial sound impact could put at risk hermit crabs and their symbiont anemones. Sci. Total Environ. 900, 165756.

de Soto, N.A., Delorme, N., Atkins, J., Howard, S., Williams, J., Johnson, M., 2013. Anthropogenic noise causes body malformations and delays development in marine larvae. Sci. Rep. 3, 2831.

Southall, B.L., Nowacek, D.P., Bowles, A.E., Senigaglia, V., Bejder, L., Tyack, P.L., 2021. Marine mammal noise exposure criteria: assessing the severity of marine mammal behavioral responses to human noise. Aquat. Mamm. 47 (5), 421–464.

Stephan, C.E., Mount, D.I., Hansen, D.J., Gentile, J.H., Chapman, G.A., Brungs, W.A., 2017. Guidelines for Deriving Numerical National Water Quality Criteria for the Protection of Aquatic Organisms and Their Uses. U.S. Environmental Protection Agency. EPA-822-R-17-001.

Taylor, J.J., McIntosh, R.R., Gray, R.B., Charrier, I., 2024. Behavioural response of Australian fur seals (*Arctocephalus pusillus doriferus*) to vessel noise during peak and off-peak human visitation. Mar. Pollut. Bull. 208, 116947.

Tennessen, J.B., Holt, M.M., Wright, B.M., Hanson, M.B., Emmons, C.K., Giles, D.A., Hogan, J.T., Thornton, S.J., Deecke, V.B., 2024. Males miss and females forgo: Auditory masking from vessel noise impairs foraging efficiency and success in killer whales. Glob. Chang. Biol. 30 (9), e17490.

Vasconcelos, R.O., Amorim, M.C.P., Ladich, F., 2007. Effects of ship noise on the detectability of communication signals in the Lusitanian toadfish. J. Exp. Biol. 210 (12), 2104–2112.

Vergara, V., Mikus, M.A., Chion, C., Lagrois, D., Marcoux, M., Michaud, R., 2025. Effects of vessel noise on beluga (*Delphinapterus leucas*) call type use: Ultrasonic communication as an adaptation to noisy environments? Biol. Open 14 (3), bio061783.

Vieira, M., Beauchaud, M., Amorim, M.C.P., Fonseca, P.J., 2021. Boat noise affects meagre (*Argyrosomus regius*) hearing and vocal behaviour. Mar. Pollut. Bull. 172, 112824.

Wale, M.A., Briers, R.A., Hartl, M.G., Bryson, D., Diele, K., 2019. From DNA to ecological performance: Effects of anthropogenic noise on a reef-building mussel. Sci. Total Environ. 689, 126–132.

Wang, W., Turco, T., Pradeau, A., Fonseca, P.J., Vasconcelos, R.O., Amorim, M.C.P., Coureaud, G., Beauchaud, M., 2025b. Long-term boat noise effects on growth and behavioural patterns during early life stages of the African cichlid Maylandia zebra. Freshw. Biol. 70 (8), e70077.

Wang, Z., Jin, R., Xu, P., Wang, B., Gul, S., Shang, Y., Hu, M., Yang, Q., Huang, W., Wang, Y., 2025a. Physiological and behavioral effects of underwater noise on the large yellow croaker (*Larimichthys crocea*) and the blackhead seabream (*Acanthopagrus schlegelii*). Aquaculture 602, 742318.

Weilgart, L.I.N.D.Y., 2018. The Impact of Ocean Noise Pollution on Fish and Invertebrates. Report for OceanCare, Switzerland.

Williams, R., Wright, A.J., Ashe, E., Blight, L.K., Bruintjes, R., Canessa, R., Clark, C.W., Cullis-Suzuki, S., Dakin, D.T., Erbe, C., Hammond, P.S., Merchant, N.D., O'Hara, P. D., Purser, J., Radford, A.N., Simpson, S.D., Thomas, L., Wale, M.A., 2015. Impacts of anthropogenic noise on marine life: Publication patterns, new discoveries, and future directions in research and management. Ocean Coast. Manag. 115, 17–24.

Wysocki, L.E., Dittami, J.P., Ladich, F., 2006. Ship noise and cortisol secretion in European freshwater fishes. Biol. Conserv. 128 (4), 501–508.

Xu, R., Yang, S., Li, Y., Zhang, X., Tang, X., 2025. Boat noise increases the oxygen consumption rate of the captive juvenile large yellow croaker, *Larimichthys crocea*. Animals 15 (5), 714.