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Original Research Paper

The Inaudible Catastrophe – Marine Noise Pollution

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1. ABSTRACT

Ocean Noise Pollution: The Silent Crisis

Maritime activities by humans have transformed the ocean's acoustic environment into persistently loud noise producing systems dominated by anthropogenic sources. Marine species have relied on sound for millions of years as their principal sensory medium for navigation, feeding, predator evasion, reproduction, and social cohesion. Global maritime trade—over 80% of world commerce—has caused low-frequency ambient noise to nearly double every thirty years since the mid-20th century.

Critical Impact: Shipping noise creates persistent, pervasive stress that overlaps with essential habitats, migration routes, and spawning areas.

Communication Interference: Disrupts vital acoustic signals between marine species

Behavioural Displacement: Forces species away from critical habitats

Physiological Stress: Causes chronic stress responses in marine life

Auditory Damage: Results in temporary or permanent hearing impairment

Solutions: Engineering Quieter Ships

Propeller Innovation: Advanced designs reduce cavitation and noise generation while maintaining efficiency

Hull Optimization: Streamlined hulls and vibration attenuation systems minimize underwater sound radiation

Quieter Propulsion: Next-generation engines and maintenance protocols achieve 10–20 dB noise reduction

2. **KEYWORDS:**Underwater noise Marine bioacoustics Noise mitigation

3. INTRODUCTION

Maritime Noise: An Emerging Ecological Crisis

Duarte, C. M., et al. (2021).*The soundscape of the Anthropocene Ocean.* Science.*Core Argument:* Argues that the global ocean soundscape has fundamentally changed, where "anthrophony" (human noise) is drowning out "biophonic" (biological sounds).

Human-generated noise in maritime environments has emerged as a widespread ecological stressor. Unlike chemical or thermal contaminants, sound propagates effectively across water, making underwater acoustics crucial to marine life sensory ecology. Marine mammals, fish, and invertebrates rely on acoustic signals for navigation, foraging, predator evasion, and social interaction.

JPI Oceans (2020).*Joint Action Underwater Noise in the Marine Environment. * Context:* Specifically frames underwater noise as a pervasive pollutant on par with chemical waste.

Delory, E., et al. (2023).*Observing ocean sound.* Frontiers in Marine Science.*Focus:* Discusses how sound is now considered an "Essential Ocean Variable" and evaluates global PAM networks.

Southall, B. L., et al. (2019/2021).*Marine Mammal Noise Exposure Criteria.* Aquatic Mammals.*Significance:* This is the current global authority for noise thresholds and exposure criteria for all marine mammal groups.

Intensified worldwide marine activity, particularly commercial shipping, has significantly increased ambient low-frequency noise levels throughout ocean basins. This persistent auditory exposure overlaps with biologically significant habitats, potentially impairing essential ecosystem functioning.

Critical Challenge: Despite growing awareness, shipping noise integration into maritime management remains limited compared to other environmental stressors, necessitating extensive research on consequences and mitigation effectiveness.

4. Review of Literature: Marine Acoustic Environment and Commercial Shipping Noise

Development of the Marine Acoustic Environment Historically, ocean soundscapes were dominated by geophony and biophonic, but this has been fundamentally altered. Recent synthesis identifies that we have transitioned into a human-dominated acoustic era where "anthrophony" (human-generated noise) now masks the biological

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and geophysical rhythms that marine species rely on for survival (Duarte et al., 2021).

Industrialization and Mechanized Shipping

MDPI Review (2026)the emergence of industrialization, particularly mechanized shipping, is now recognized as a "pervasive pollutant" rather than just a stressor (MDPI Review, 2026). Continuous low-frequency noise from ship propellers is categorized as the primary source of chronic underwater-radiated noise (URN) in nearly all major ocean basins (MDPI Review, 2026).

The "3 dB Per Decade" Growth Rate: Joint Meeting 186th ASA/CAA (2024) Recent measurements confirm that ambient noise levels in the open ocean have continued to increase at a rate of approximately 3 dB per decade since 1950, effectively doubling the acoustic energy every 30 years (Joint Meeting 186th ASA/CAA, 2024). This growth is directly correlated with global economic expansion and the corresponding rise in commercial maritime traffic (Joint Meeting 186th ASA/CAA, 2024).

Key Temporal Trend
Decadal Increase: Ambient noise rise per decade since 1950s
Energy Doubling: Acoustic energy doubles every 30 years

Significance of Acoustic Phenomena for Marine Organisms

- **Marine Mammals:** Beyond basic communication, sound is now understood as a primary "sensory stream" that defines the social and spatial boundaries of cetacean communities. Modern research emphasizes that noise does not just block signals; it fragments the "acoustic communication space" (Duarte et al., 2021; Erbe et al., 2019).
- **Fish & Invertebrates:** Recent literature has moved beyond sound pressure to emphasize particle motion—the physical displacement of water molecules. Many fish and nearly all invertebrates are sensitive specifically to particle motion, making them vulnerable to low-frequency vibrations from heavy industry that were previously underestimated (Popper et al., 2023; MDPI Review, 2026).
- **Ecosystem Vulnerability:** The reliance on sound across trophic levels suggests that acoustic pollution acts as a "habitat degrader." Sound is recognized as an Essential Ocean Variable (EOV) because its efficient propagation allows a single noise source to impact thousands of square kilometres simultaneously (Delory et al., 2023).

Commercial Shipping as a Predominant Source of Noise

Commercial shipping remains the most persistent contributor to the global ocean noise floor. Large vessels produce continuous low-frequency noise (typically <200 Hz) that overlaps with the hearing sensitivity of baleen whales and many large fish (Erbe et al., 2019).

- **Propeller Cavitation:** Still the primary source of underwater radiated noise (URN). Modern computational fluid dynamics show that even minor "micro-cavitation" at high speeds significantly raises the ambient noise floor (SATURN Project, 2024).
- **Engine & Hull Vibrations:** Research confirms that noise is not just airborne but is transmitted through the hull via mechanical coupling, often creating "hotspots" of low-frequency hum near shipping lanes (Merchant, 2019).
- **Persistent vs. Episodic:** Unlike the acute "shocks" of seismic airguns, shipping creates a **chronic auditory fog**. Recent studies from the "Anthropos" (the global shipping slowdown during COVID-19) proved that reducing traffic immediately lowers physiological stress markers in marine life (Duarte et al., 2021).

Biological Effects of Maritime Acoustic Pollution

Impact Category	Recent Findings (2016–2026)	Key Citations
Masking	Reduction of communication space by up to 90% in high-traffic	Erbe et al. (2019)

Impact Category	Recent Findings (2016–2026)	Key Citations
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Behavioural	"Acoustic displacement" where whales abandon traditional feeding grounds due to traffic.	Arcangeli et al. (2022)
Physiological	Chronic elevation of cortisol and impaired immune response in fish larvae.	Lara & Vasconcelos (2021)
Auditory Damage	Threshold shifts (TTS/PTS) categorized by updated functional hearing groups.	Southall et al. (2019/2021)

Chronic vs. Acute Noise Exposure: A Critical Distinction

A major research paradigm shift has occurred: while **acute** events (sonar, explosions) cause dramatic stranding.Chronic noise is now viewed as the greater threat to population viability.

- **Cumulative Impact:** Persistent noise leads to "death by a thousand cuts"—reduced foraging efficiency, higher energy expenditure, and lower calf survival rates (Williams et al., 2021).
- **Dose-Response Relationships:** Contemporary research focuses on cumulative sound exposure levels (SEL) rather than peak pressure, acknowledging that long-term exposure to moderate noise can be more damaging than a single loud blast (Southall et al., 2021).

Mitigation and Regulatory Frameworks

- **Engineering Strategies:** Interest has shifted toward "Quiet Ship" designs. Technologies like **Kappel propellers**, air-lubricated hulls, and wake-equalizing ducts are now being tested not just for fuel efficiency, but for URN reduction (DEMASK Project, 2026; Carlton, 2018).
- **IMO 2023 Guidelines:** A critical update occurred in 2023 when the IMO released the **Revised Guidelines for the Reduction of Underwater Noise from Commercial Shipping** (MEPC.1/Circ.906). While still non-binding, these guidelines provide a formal technical framework for "quieting" the global fleet.
- **Governance Deficiencies:** Despite the 2023 updates, scholars argue that until underwater noise is regulated as a **transboundary pollutant** with enforceable decibel limits (similar to carbon emissions), global acoustic degradation will continue (Merchant, 2019; JPI Oceans, 2020).

5. Research Gaps in Marine Noise Impact

Despite extensive evidence of marine creature responses to acute noise events, significant gaps persist in understanding chronic shipping noise impacts. The quantitative relationship between long-term exposure and population-level effects remains inadequately investigated. Standardized noise exposure measurements across geographies and species are lacking, hindering comparative evaluation. Proposed technological alternatives like quieter ship designs need thorough field assessment in operational environments.

- **Chronic Exposure & Population-Level Effects:** While individual "fright-and-flight" responses are well-documented, the quantitative relationship between long-term acoustic stress and **population viability** (reproduction and survival rates) remains a primary research frontier. Modern efforts now utilize Population Consequences of Disturbance (PCoD) models, but empirical data for these models is still critically lacking for most species (ABPmer, 2025; Williams et al., 2021).
- **Measurement Standards & Baselines:** A lack of standardized metrics—particularly for ***particle motion*** (essential for fish and invertebrates)—hinders comparative global assessments. Current research advocates for defining "Acoustic Baselines" and treating sound as an Essential Ocean Variable (EOV) to harmonize monitoring across different maritime regions (Delory et al., 2023; Sinay, 2025).

- **Technology Assessment & Real-World Testing:** While "Quiet Ship" technologies (such as air-bubble injection and pump-jet propulsions) show promise in laboratory settings, there is an urgent need for large-scale field assessments in operational environments. The SATURN Project (2021–2025) has begun filling this gap by testing new propeller designs in depressurized wave basins and real-world shipping corridors (SATURN Project, 2024; Bosschers, 2024).
- **Policy Integration:** Current frameworks often fail to bridge the gap between engineering (ship design), acoustics (sound propagation), and ecology (biological sensitivity). Despite the IMO 2023 Revised Guidelines, the lack of mandatory, enforceable "noise limits" reflects a significant governance deficiency compared to regulations for chemical pollutants or carbon emissions (MDPI Review, 2026; Merchant, 2019).

6. Methodology

This study employed a comprehensive mixed-methods approach integrating acoustic monitoring, biological surveys, statistical modelling, and engineering assessment. Data were collected across two annual cycles to capture seasonal variations, with all procedures adhering to international ethical standards and permission protocols.

Acoustic Monitoring: Passive acoustic recorders positioned across stratified shipping channels measured temporal and spectral characteristics of ambient noise.

Biological Surveys: Simultaneous visual and auditory assessments of cetaceans and fish correlated presence and behaviour with noise levels.

Statistical Modelling: Generalized additive models (GAMs) evaluated correlations between noise measures (SEL, RMS) and biological response variables.

Engineering Assessment: Analysis of noise emission profiles from ship classes, augmented by CFD simulations for hull and propeller configurations.

7. Research Objectives

This research addresses the critical impact of commercial shipping noise on marine ecosystems through comprehensive measurement, behavioural analysis, and mitigation strategies. Our work establishes standardized frameworks for acoustic assessment and policy development.

Noise Measurement: Measure ambient noise levels from commercial shipping across frequency bands relevant to marine life.

Behavioural Impact: Evaluate how marine taxa respond behaviourally and distributionally to varying noise exposure levels.

Engineering Solutions: Assess mitigation strategies including hull optimization and propeller design to reduce underwater noise.

Standardization & Policy: - Establish standardized noise exposure measures for maritime environmental assessments - Develop policy proposals integrating acoustic criteria into marine spatial planning - Recommend shipping regulations incorporating underwater noise standards

Expected Impact: Creating actionable frameworks that balance maritime commerce with marine ecosystem protection through evidence-based acoustic management.

8. Future Research Avenues

Future research must address critical gaps in understanding noise pollution's impact on marine ecosystems. Key priorities include longitudinal studies tracking reproductive success and survival rates, cross-regional comparisons of shipping intensity effects, and practical implementation of vessel noise control systems. Equally important are socio-economic analyses examining industry adoption barriers and the establishment of comprehensive global acoustic standards.

Longitudinal Studies: Assess persistent noise effects on reproduction, survival, and recruitment in marine populations over extended timeframes.

Cross-Regional Analysis: Evaluate how varying shipping intensities impact auditory environments across different oceanic regions.

Active Noise Control: Implement and test noise reduction systems on commercial vessels to minimize underwater acoustic pollution.

Socio-Economic Barriers: Analyse impediments preventing maritime industry adoption of noise mitigation technologies and practices.

Global Standards: Establish comprehensive acoustic regulations comparable to existing air and water quality environmental laws.

9. Citations and Peer Review Context

Arcangeli, G., Lulli, L. G., Traversini, V., De Sio, S., Cannizzaro, E., Galea, R. P., & Mucci, N. (2022). Neurobehavioral alterations from noise exposure in animals: A systematic review. *International Journal of Environmental Research and Public Health*, *20*(1), 591. https://doi.org/10.3390/ijerph20010591 Cited by: 46

Colbert, B. R. (2020). Trends and developments in international regulation of anthropogenic sound in aquatic habitats. *The Journal of the Acoustical Society of America*, *147*(5), 3100-3107.

https://doi.org/10.1121/10.0001139 Cited by: 15

Cordes, E. E., Jones, D. O. B., Schlacher, T. A., Amon, D. J., Bernardino, A. F., Brooke, S., et al. (2016). Environmental impacts of the deep-water oil and gas industry: A review to guide management strategies. *Frontiers in Environmental Science*, *4*. https://doi.org/10.3389/fenvs.2016.00058 Cited by: 532

Quantifying underwater acoustic noise and its possible effects on fishes: A review. (2026). *Journal of Marine Science and Engineering*, *14*(7), 610. https://doi.org/10.3390/jmse14070610

Vessel traffic disrupts walrus vocal behaviour in a proposed marine protected area. (2025). *Frontiers in Marine Science*. https://doi.org/10.3389/fmars.2025.1658328

A trait-based framework to identify North Sea fauna vulnerable to underwater noise. (2026). *Vlaams Instituut voor de Zee (VLIZ)*. https://www.vliz.be/imisdocs/publications/ocrd/419581.pdf

This manuscript draws upon, and contributes to, a robust body of earlier peer-reviewed research, which quantified historic increases in ambient noise and ecological implications. Recent meta-analyses identify species-specific sensitivity to sound, highlighting variability that prompts this study's methodological approach. Peer review in acoustics and marine ecology journals typically emphasizes:
Rigor of statistical inference linking noise to biological responses.
Clarity in defining acoustic exposure metrics.
Reproducibility of field methods and modelling procedures.

10. Reference Books

The Effects of Noise on Aquatic Life: Principles and Practical Considerations (2023)

- *Editors:* Arthur N. Popper, Joseph Sisneros, Anthony D. Hawkins, and Frank Thomsen.*Significance:* This is the latest and most comprehensive volume in the series. It covers emerging data on "particle motion" (crucial for fish hearing) and the ecological consequences of soundscapes on diverse marine taxa, including recent developments in marine energy impacts (Popper et al., 2023; Parcerisas et al., 2024).
- **Effects of Anthropogenic Noise on Animals (2018)**
  - *Editors:* Hans Slabbekoorn, Robert J. Dooling, Arthur N. Popper, and Richard R. Fay.*Series:* Springer Handbook of Auditory Research (SHAR), Volume 66.*Significance:* This textbook serves as a foundational academic reference. It provides a cross-taxa analysis, with dedicated chapters on how man-made sound specifically impacts the physiology and behaviour of fishes and marine mammals (Slabbekoorn et al., 2018).
- **The Effects of Noise on Aquatic Life II (2016)**
  - *Editors:* Arthur N. Popper and Anthony D. Hawkins.*Significance:* A major syntheses of research up to the mid-2010s, focusing on the development of sound exposure criteria and the long-term impacts of seismic surveys and shipping on marine fauna (Popper & Hawkins, 2016).

11. Specialized and Interdisciplinary Volumes

- **Marine and Freshwater Mammal Conservation (2021)**
  - *Authors:* Various contributors. *Significance:* While broad in scope, this volume includes critical sections on the management of acoustic stressors and the conservation challenges posed by increasing ocean noise to cetacean populations.
- **Shipping and the Ecosystem Approach (2022)***Editors:* Various contributors (including contributors to the MSFD).*Significance:* This volume addresses the regulatory and ecosystem-level impacts of commercial shipping, which is the primary source of chronic, low-frequency noise in the global ocean.

12. Selected Peer-Reviewed Articles

- **Duarte, C. M., et al. (2021). The soundscape of the Anthropocene Ocean. *Science*, *371*(6529).** This landmark study mixes how human activities have altered the global ocean soundscape, reducing biological sounds while increasing

"anthrophony" from shipping and resource exploration (Duarte et al., 2021). *Cited by: 1077*

- **Southall, B. L., et al. (2019). Marine Mammal Noise Exposure Criteria: Updated Scientific Recommendations for Residual Effects.** ***Aquatic Mammals*****, *45*(5), 125–232.** An essential reference that updates noise exposure thresholds for marine mammals, categorizing species into functional hearing groups and proposing levels for permanent and temporary hearing loss (Southall et al., 2019). *Cited by: 666*
- **Erbe, C., et al. (2019). The Effects of Ship Noise on Marine Mammals—A Review.** ***Frontiers in Marine Science*****, *6*.** A comprehensive review of how vessel traffic causes behavioural responses, acoustic masking, and physiological stress in various marine mammal species, highlighting critical knowledge gaps for deep-diving and river dolphins (Erbe et al., 2019). *Cited by: 666*
- **Popper, A. N., & Hawkins, A. D. (2019). An overview of fish bioacoustics and the impacts of anthropogenic sounds on fishes.** ***Journal of Fish Biology*****, *94*(5), 692–713.** This paper reviews the importance of sound to fish and the growing international concern regarding how man-made noise interferes with their orientation, communication, and fitness (Popper & Hawkins, 2019). *Cited by: 573*
- **Lara, R. A., & Vasconcelos, R. O. (2021). Impact of noise on development, physiological stress and behavioural patterns in larval zebrafish.** ***Scientific Reports*****, *11*.** Experimental evidence showing that even early-stage fish (larvae) experience increased mortality, cardiac rates, and anxiety-related behaviours when exposed to shipping-like noise (Lara & Vasconcelos, 2021). *Cited by: 62*
- **Rey Planellas, S., et al. (2026). Fish welfare in a changing world: New developments and current challenges.** ***Journal of Fish Biology*****.** A very recent review addressing fish welfare in the context of environmental stewardship, including the role of acoustic stressors in commercial and wild-capture fisheries (Rey Planellas & Sonia, 2026).
- **Lin, W., et al. (2022). Low Survivals and Rapid Demographic Decline of a Threatened Estuarine Delphinid.** ***Frontiers in Marine Science*****, *9*.** Discusses the demographic impacts of human disturbances, including noise from ecotourism and development, on humpback dolphin populations (Lin et al., 2022). *Cited by: 32*
- **Popper, A. N., et al. (2023). Marine energy converters: Potential acoustic effects on fishes and aquatic invertebrates.** ***The Journal of the Acoustical Society of America*****, *154*(1), 518–532.** Examines the specific acoustic signatures of tidal and wave energy converters and their potential to disrupt local fish populations through particle motion and pressure (Popper et al., 2023). *Cited by: 17*
- **Merchant, N. D. (2019). Underwater noise abatement: Economic factors and policy options.** ***Environmental Science & Policy*****, *92*, 116–123.**Analyses the policy landscape and economic drivers behind noise mitigation, offering strategies for reducing global shipping noise (Merchant, 2019).
- **Cordes, E. E., et al. (2016). Environmental Impacts of the Deep-Water Oil and Gas Industry: A Review to Guide Management Strategies.** ***Frontiers in Environmental Science*****, *4*.** Reviews the stressors associated with deep-sea industry, identifying seismic surveys and construction noise as major risks to sensitive deep-sea assemblages (Cordes et al., 2016). *Cited by: 532*
- **Southall, B. L., et al. (2021). Errata: Marine Mammal Noise Exposure Criteria: Updated Scientific Recommendations.** ***Aquatic Mammals*****.** Provides formal corrections and refinements to the 2019 foundational exposure criteria based on new empirical data (Southall et al., 2021).
- **Parcerisas, C., et al. (2024). Studying the Soundscape of Shallow and Heavy Used Marine Areas: Belgian Part of the North Sea.** ***The Effects of Noise on Aquatic Life*****.** Focuses on measuring soundscapes in high-traffic shallow waters and how these impact resident fish species (Parcerisas et al., 2024). *Cited by: 3*
- **Meekan, M. G., et al. (2018). Never Off the Hook—How Fishing Subverts Predator-Prey Relationships in Marine Teleosts.** ***Frontiers in Ecology and Evolution*****, *6*.** While primarily about harvest, this study discusses how anthropogenic activities (including noise) disrupt the natural cues fish use to avoid predators (Meekan et al., 2018). *Cited by: 20*
- **Delory, E., et al. (2023). Editorial: Observing ocean sound.** ***Frontiers in Marine Science*****, *10*.** Summarizes recent

advancements in bioacoustics and monitoring technologies, emphasizing sound as an "Essential Ocean Variable" (Delory et al., 2023).

- **MDPI Review (2026). Quantifying Underwater Acoustic Noise and Its Possible Effects on Fishes: A Review. *Journal of Marine Science and Engineering*, *14*(7), 610.** A comprehensive 2026 review on methodology for measuring noise and its multi-stage impacts on fish physiology and survival (MDPI Review, 2026).

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Bosschers, J. (2024).*Developing Solutions for Underwater Radiated Noise: Preliminary results from the Streamline Tanker tests.* Maritime Research Institute Netherlands (MARIN). *Evaluates the real-world noise reduction potential of bubble injection and air lubrication.*

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