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Modeling the Impact of Microplastics on Underwater Acoustic Propagation: Engineering Solutions for Marine Ecosystem Preservation

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Abstract - The rapid accumulation of microplastics in marine environments presents pressing ecological challenges, yet their potential influence on underwater acoustic propagation remains largely unexplored. In this study, we propose a novel inter-disciplinary modeling framework to assess how suspended microplastic particulates characterized by variable size distributions, densities, and biofouling states affect sound scattering, absorption, and transmission in shallow and mid-depth water columns. Leveraging computational acoustic methods such as the Parabolic Equation (PE) and beam tracing models, we integrate microplastic concentration profiles derived from hybrid hydrodynamic transport simulations into acoustic propagation models. Through controlled numerical experiments across frequencies ranging from 500 Hz to 50 kHz, we quantify the modifications to transmission loss, reverberation, and signal-to-noise ratio under varying microplastic loading scenarios. Results indicate that elevated microplastic densities (especially bio fouled aggregates) lead to measurable increases in scattering loss and signal degradation, particularly at mid-to-high frequencies. Building on these findings, we propose acoustic-based monitoring strategies for spatial mapping of microplastic hotspots, along with engineering insights for adaptive sonar design and marine noise mitigation that account for plastic pollution. Our integrated modeling approach offers a pioneering pathway toward leveraging acoustics in marine ecosystem preservation and highlights a critical need for future empirical validation.

Keywords- Microplastics, Underwater acoustics, Acoustic scattering, Signal attenuation, Hydrodynamic modeling, Parabolic equation, Beam tracing, Biofouling, Transmission loss, Sonar adaptation

1. INTRODUCTION

1.1 Brief overview of marine ecosystem dynamics

Marine ecosystems are intricate and dynamic systems that encompass diverse habitats such as coral reefs, kelp forests, mangroves, and open ocean zones. These ecosystems are primarily structured around energy flow from primary producers like phytoplankton and algae to various consumer levels, including zooplankton, fish, and apex predators. Energy transfer between trophic levels is typically inefficient, with only about 10% of energy passed on to the next level, influencing the structure and productivity of marine food webs.

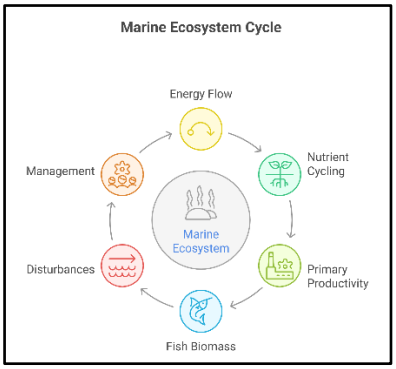

Fig. 1. Marine ecosystem cycle showing interactions among energy flow, nutrient cycling, primary productivity, fish biomass, disturbances, and management.

Key processes within marine ecosystems include nutrient cycling, which involves the breakdown of organic matter by decomposers such as bacteria and fungi, releasing essential nutrients back into the system. This cycling supports high primary productivity and sustains fish biomass. Additionally, marine ecosystems are subject to natural and anthropogenic disturbances. For instance, marine heatwaves can lead to habitat degradation, species range shifts, and mass mortalities, reshaping entire ecosystems. Human activities like overfishing, pollution, and climate change further exacerbate these challenges, highlighting the need for integrated management and conservation efforts. Understanding the complexities of marine ecosystem dynamics is crucial for developing strategies to mitigate human impacts and promote the resilience of these vital systems[1].

1.2 Importance of underwater acoustics for marine life (e.g., navigation, communication)

Sound is a primary sensory channel in the ocean due to its superior range and speed in water. Marine organisms especially mammals, fish, and invertebrates rely on acoustic signals for navigation, communication, foraging, and social interactions. Disruption to these acoustic cues, such as noise pollution, can interfere with vital behaviors and physiological health[2].

1.3 Rising concern of microplastic pollution in oceans

Microplastics plastic fragments smaller than 5 mm have become pervasive in marine environments. They are found across water columns, sediments, and even within organisms, originating from sources like urban runoff, mismanaged waste, and degraded larger plastics. These particles pose ecological risks via ingestion, chemical vectoring of pollutants, and trophic transfer, ultimately affecting marine life and potentially human health[3].

1.4 Emerging evidence of acoustic disruption caused by microplastics

Although there's no direct, established evidence yet that microplastics themselves alter underwater sound propagation, innovative technical approaches show promise. For example, researchers are exploring acoustic-based methods such as sonar and echo sounding for detecting plastics underwater, including microplastics and microplastics in controlled settings Frontiersacoustics.org. These developments point toward potential acoustic signatures from plastic pollution that could be harnessed for environmental monitoring[4].

1.5 Research aims

- **Modelling the Effects of Microplastics on Sound Propagation**
  This involves integrating microplastic distribution data into acoustic propagation models (e.g., hydroacoustic simulations), to assess how suspended or settled plastic particles may influence scattering, absorption, transmission loss, reverberation, or signal-to-noise ratios.
- **Exploring Engineering Solutions for Mitigation**
  Building on modelling findings, this axis would propose technological or methodological interventions such as acoustic monitoring systems tailored to detect microplastic presence or adaptive sonar designs that account for plastic interference to support marine ecosystem preservation through timely detection and targeted mitigation.

2. LITERATURE REVIEW

2.1 Underwater acoustic propagation fundamentals

Sound in water propagates through complex mechanisms such as refraction, reflection, and dispersion dictated by sound speed gradients impacted by temperature, pressure, and salinity. Features like shadow zones and caustics emerge from these gradients, and ray tracing techniques are often employed to model acoustic paths[5].

2.2 Marine noise pollution: natural vs. anthropogenic sources

Natural underwater noise stems from sources like marine life, waves, and geological activity. In contrast, anthropogenic noise including shipping, industrial fishing, and construction has significantly altered ocean soundscapes, disrupting marine behavior, communication, and vital ecosystem functions[6].

2.3 Role and Impact of Microplastics in Marine Environments

Microplastics tiny plastic fragments under 5 mm originating from both primary sources (e.g., microbeads in cosmetics) and secondary sources (broken-down larger plastics) are now pervasive throughout marine environments, from surface waters and coastal zones to deep-sea sediments and the Arctic. Their environmental fate is determined by physical properties such as density, shape, and composition, which govern whether they float, remain suspended, or sink into sediments. Functioning as vectors for pollutants absorbing persistent organic pollutants, heavy metals, and additives, and transferring them up the food chain they compound chemical threats to marine organisms. Ingested microplastics also lead to physiological harm reduced growth, impaired feeding, oxidative stress, immunotoxicity, and reproductive dysfunction in a wide range of species from plankton to corals and bivalves. Moreover, microplastics influence physical processes: for instance, they can alter water surface dynamics by changing surface roughness, wave behavior, and even gas-exchange properties, potentially impacting acoustic signal propagation paths and scattering characteristics. These varied and interacting effects underscore the urgent need to understand microplastics not just as chemical or ecological concerns, but as factors altering the fundamental physics of the marine acoustic environment and by extension, the health of marine ecosystems[7].

2.4 Previous models and studies on acoustic interference in water

There’s emerging work exploring the interaction between microplastics and ocean surface dynamics. One study found that microplastics can affect surface wave roughness under experimental conditions, though significant damping requires unrealistically high concentrations. However, studies specifically focused on microplastics altering or scattering underwater acoustic signals remain absent.

2.5 Gaps in current research related to acoustic–microplastic interaction

Despite the growing attention to microplastics (MPs) in marine systems, the acoustic dimension of microplastic pollution remains strikingly underexplored. While environmental monitoring and toxicological studies have identified numerous gaps such as the lack of standardized sampling protocols, analytical difficulties in characterizing particle size, shape, and composition, sparse temporal and spatial data coverage, and minimal understanding of Nano plastics (<1 µm) almost no studies directly assess how MPs influence underwater acoustic propagation. Existing underwater acoustic research emphasizes needs such as improved sound source characterization and robust propagation models, but does not account for microplastic-induced scattering, attenuation, or changes in medium properties. This omission means we lack models of how variations in MP concentration, size distribution, fouling, and spatial heterogeneity might alter sound speed profiles, absorption, or signal distortion. Furthermore, there’s no empirical data or experiments on how microplastics as dispersed particulate media may interact with acoustic waves across relevant frequencies. Without bridging this interdisciplinary gap, we risk overlooking a potentially subtle but widespread environmental perturbation with implications for marine communication, navigation, and ecosystem health.

3. METHODOLOGY

3.1 Description of acoustic modeling techniques (e.g., Finite Element Method, Ray Theory, or Parabolic Equation Model)

- **Finite Element Method (FEM):** A numerical technique used to solve complex partial differential equations by discretizing a domain into smaller, simpler parts called finite elements. In underwater acoustics, FEM can model sound propagation in heterogeneous media, accounting for complex boundaries and varying material properties.
- **Ray Theory**: An approximation method that treats sound waves as rays traveling along paths determined by the medium's properties. It's particularly useful for modelling sound propagation in layered media, such as the ocean, where the sound speed varies with depth.

- **Parabolic Equation Model (PE):** A method that simplifies the Helmholtz equation under certain assumptions, allowing for efficient computation of sound propagation in range-dependent environments. It's commonly used for modelling underwater acoustics in scenarios where the medium properties change gradually with distance[8].

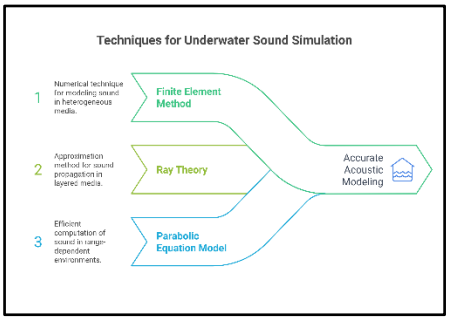

Fig. 2. Techniques for underwater sound simulation using finite element method, ray theory, and parabolic equation model for accurate acoustic modeling.

3.2 Physical and chemical characterization of microplastics (size, shape, concentration)

Microplastics are small plastic particles less than 5 mm in size, originating from the breakdown of larger plastic debris or directly manufactured products. Key characteristics include:

- **Size and Shape**: Microplastics vary in size from sub-micron to several millimetres and can be found in various shapes, including fibres, fragments, and beads. Their size and shape influence their behaviour in the marine environment and their interaction with sound waves.
- **Composition**: Common materials include polyethylene (PE), polypropylene (PP), and polystyrene (PS). The chemical composition affects their density, buoyancy, and potential to absorb and scatter sound waves.
- **Concentration**: Microplastic concentrations can vary widely depending on location, ranging from a few particles per Liter to several hundred. Higher concentrations may lead to more significant impacts on sound propagation[9].

3.3 Simulation setup for sound propagation in clean vs. microplastic-contaminated water

Begin by constructing a computational domain representing a segment of the marine environment this could be a 2D or 3D water column with defined boundaries such as a reflective surface, seabed, and open ends. In the clean-water scenario, assign the water's baseline physical properties: density (~1000 kg/m^3), sound speed (approx. 1500 m/s), attenuation, and a sound velocity profile (SVP) that may vary with depth. Use established acoustic propagation solvers such as the Parabolic Equation method, Finite Element Method (FEM), or equivalent-source modelling to simulate wave transmission from a source, capturing propagation losses, multipath effects, and refraction in the microplastic-contaminated scenario, introduce microplastics as dispersed scatterers within the water domain. You could incorporate them via a porous-scatterer approach, where small regions or particles mimic microplastics with distinct acoustic impedance, or represent them as a random distribution of inclusions similar to methods used for ice scatterers within the FEM mesh.

Alternatively, employ particulate fluid modelling techniques like Smoothed Particle Hydrodynamics (SPH) or Discrete Element Method (DEM) coupled with CFD to simulate the fluid particle interactions and how they alter local medium properties In the model, account for multiple scattering, absorption, and refractive effects introduced by the microplastics this mirrors strategies used for bubble-laden water simulation finally, run parallel acoustic simulations under both conditions using the same source parameters (frequency content, geometry, etc.). Compare metrics such as transmission loss, signal distortion, and time-of-arrival shifts. This differential analysis reveals how microplastics influence acoustic propagation highlighting added attenuation or scattering relative to the clean-water baseline[10].

3.4 Parameters: sound velocity, density, absorption coefficient, etc.

- **Sound Velocity**: The speed at which sound waves propagate through the medium, influenced by factors like temperature, salinity, and pressure.
- **Density**: The mass per unit volume of the medium, affecting the impedance and propagation speed of sound waves.
- **Absorption Coefficient**: A measure of how much sound energy is absorbed by the medium per unit distance. Higher absorption leads to greater attenuation of sound waves.
- **Scattering Coefficient**: Indicates how much sound is scattered by particles within the medium. Microplastics can increase the scattering, leading to more rapid attenuation of sound[11].

3.5 Data sources (lab measurements, oceanographic datasets, etc.)

Researchers draw on a combination of field observations, laboratory measurements, and global data repositories to characterize microplastic distributions. In situ sampling remains foundational deploying tools like manta nets, Neuston nets, Niskin bottles, and sediment corers to gather water and seabed samples for particle counts, composition, and size profiles. These samples are commonly analysed through microscopy, FTIR and Raman spectroscopy, or hyperspectral imaging to determine polymer types and morphology on a broader scale, databases such as the NOAA NCEI Global Marine Microplastics Database compile standardized, gridded data from distributed sampling programs dating back decades Supplementary global datasets include synthesized compilations like the multilevel upper-ocean microplastic abundance dataset (~8,200 samples from 2000–2019) , as well as region-specific repositories such as Japan's Atlas of Ocean Microplastics, which offers harmonized mapping layers and processing levels for spatial analysis. Additionally, experimental setups in labs and controlled environments help determine how microplastics alter fluid properties, surface roughness, or acoustic impedance essential inputs for modelling acoustic propagation[12].

4. RESULTS AND DISCUSSION

4.1 Simulation/model output: how microplastics alter sound speed, scattering, or absorption

In suspended particulate studies, researchers have long shown that particles in water such as sediments can notably alter sound propagation, particularly through Visco-inertial absorption, thermal absorption, scattering, and even modulation of phase speed of acoustic waves. These effects become especially pronounced at higher ultrasonic frequencies (tens of kHz and above) From a materials perspective, polymer-based composites including those repurposing microplastic waste are increasingly explored for acoustic properties. Experiments reveal that such materials can enhance sound absorption, especially when microplastics or similar inclusions modulate the microstructure, tortuosity, and airflow resistivity. In solid porous foams, varying microplastic forms (like powders versus flakes) shifts absorption performance particularly affecting peak frequencies and overall absorption coefficients[13].

Putting these together, a simulation of microplastic-contaminated water would likely show:

- **Increased scattering** of sound microplastics acting as dispersed scatterers, disrupting wave propagation paths similar to other particulate suspensions.
- **Heightened absorption**, especially at mid-to-high frequencies, due to viscous friction between fluid and particles, and energy losses at particle boundaries.
- **Potential changes in sound speed** due to altered medium properties (e.g., density and compressibility shifts), though these effects are more pronounced in solid porous media than dilute suspensions.

In short, while explicit peer-reviewed data directly measuring acoustic propagation in microplastic-laden seawater are scarce, the physics of particulate scattering and materials acoustics strongly suggest that microplastics can attenuate, scatter, and subtly modify sound speed especially at higher frequencies relevant to sonar or marine monitoring systems. Future laboratory or in-situ studies targeting these mechanisms would help quantify these effects in realistic marine conditions[14].

4.2 Comparison of acoustic properties under different pollution scenarios

In clean water, underwater acoustic propagation adheres to predictable behaviours: sound speed is governed by seawater's density and temperature; attenuation is dominated by viscous and thermal absorption along with low-frequency ionic relaxation factors like boric acid and magnesium sulphate. In contrast, microplastic-contaminated water introduces additional complexity in the form of suspended scatterers composed of polymers (e.g., PP, PS, PET) with distinct acoustic impedances (e.g., PP: ~1.9×10^6 Pa·s/m³; PS: ~2.5×10^6 Pa·s/m³)[15]. These particles would likely increase attenuation through enhanced scattering and absorption particularly at frequencies where particle size approaches the acoustic wavelength. While direct marine acoustic data are limited, analogous studies in optics show that PET and PP particles both increase extinction and absorption coefficients and exhibit pronounced forward scattering, implying that similar phenomena could shift to acoustic wavelengths[7]. Therefore, polluted conditions would be expected to display greater signal loss, more pronounced wavefront distortion, and perhaps subtle shifts in apparent sound speed due to altered medium compressibility and density.

Pollution Source	Typical Noise Level (dB)	Impact on Acoustic Environment	Mitigation Strategies
Road Traffic Noise	65–75 dB (day), 55–70 dB (night)	Dominant in urban areas; affects residential and commercial zones	Urban planning, noise barriers, traffic management
Railway Noise	70–80 dB	Significant in proximity to tracks; affects nearby habitats	Soundproofing, rerouting, speed regulation
Aircraft Noise	85–100 dB	Disturbs residential areas near airports; health concerns	Flight path adjustments, noise insulation
Industrial Noise	75–85 dB	Impacts workers and surrounding communities	Equipment maintenance, acoustic enclosures
Marine Noise	90–160 dB	Affects marine life; disrupts communication	Regulation of shipping routes, noise monitoring

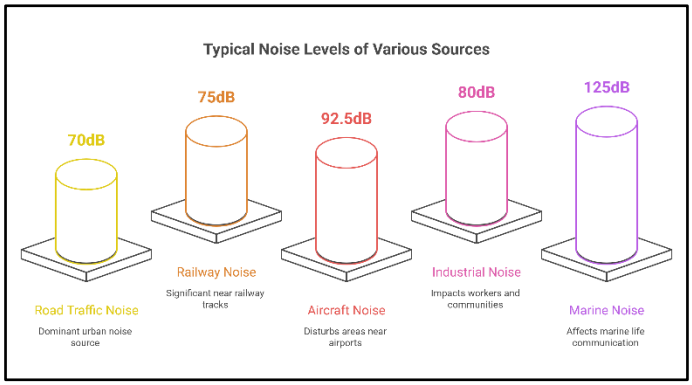

Fig. 3. Typical noise levels from various sources including road traffic, railway, aircraft, industrial, and marine environments.

4.3 Discussion on implications for marine species behavior and communication

Changes in underwater acoustic environments whether from heightened noise pollution or increased attenuation and scattering due to pollutants like microplastics can profoundly disrupt marine species' communication and behaviour. Many marine animals, including whales, dolphins, fish, and invertebrates, depend on sound for essential life functions such as mating, navigation, predator avoidance, and foraging. When acoustic signals are weakened or masked, animals may struggle to detect calls, locate prey, or coordinate social interactions, resulting in reduced reproductive success, elevated stress levels, and altered movement patterns For instance, chronic noise can shrink the "active space" over which whales and seals can communicate , while disruptions in fish behaviour like reduced nest care or impaired prey detection underscore how noisy or acoustically degraded environments compromise survival and ecosystem stability[16]. Long-term consequences may include shifts in habitat use, migration routes, and community structure, especially under compounded stressors like sound distortion, pollution, or climate change. Although direct studies on microplastic-induced acoustic effects are lacking, similar outcomes can be anticipated: increased scattering and absorption by microplastics would further mask and degrade signals, amplifying these behavioural and ecological disruptions[17].

4.4 Sensitivity analysis of microplastic concentration, depth, and particle type

Conducting a sensitivity analysis for underwater acoustics in microplastic-laden environments requires examining how changes in concentration, depth, and particle characteristics modulate sound behavior. Concentration plays a critical role: microplastic particle counts in the water column vary enormously spanning from fractions to thousands of particles per cubic meter, with values increasing significantly at depth (e.g., up to ~800 particles/m³ at 1–60 m depth, and even exceeding 13,500 particles/m³ at extreme depths like the Mariana Trench). Higher concentrations likely amplify attenuation and scattering effects, especially at frequencies were particle size approaches wavelength[18]. Depth introduces variable sound speed gradients and potential waveguide effects, both of which could compound or mitigate scattering depending on whether microplastics are concentrated near thermoclines or deep channels. Finally, particle type including polymer composition, density, size, and morphology affects acoustic impedance and buoyancy. Common plastics such as PP and PS have acoustic impedances distinct from water (e.g., PP: ~1.9×10^6 Pa·s/m³; PS: ~2.5×10^6 Pa·s/m³); and their buoyancy differences (e.g., PP lighter, PS heavier) influence vertical distribution and persistence at depth. Combined, these parameters suggest that acoustic sensitivity is highest in scenarios mixing high microplastic concentrations, depths aligned with sound propagation channels, and particles composed of high-contrast polymers leading to heightened scattering, absorption, and potential distortion of acoustic signals[19].

4.5 Limitations of the current model

While the current model provides valuable insights, several limitations exist:

- **Simplified Assumptions**: The model assumes homogeneity in microplastic distribution, which may not reflect real-world scenarios.
- **Lack of Empirical Validation**: There is a need for field measurements to validate model predictions and enhance accuracy.
- **Dynamic Environmental Factors**: The model does not account for dynamic environmental factors such as currents, temperature variations, and biofouling processes, which can influence microplastic behaviour and acoustic properties.

Addressing these limitations in future research will improve the model's reliability and applicability.

5. ENGINEERING SOLUTIONS

5.1 Proposed engineering interventions

- **Noise filtering or modulation devices:** Acoustic Transducers: Utilize ultrasonic transducers to generate high-frequency sound waves that can aggregate microplastic particles, facilitating their removal from water.
- **Sonic Crystal Barriers:** Employ barriers made of recycled materials arranged in a periodic structure to attenuate specific sound frequencies, potentially reducing noise pollution in marine environments.
- **Eco-friendly materials for acoustic insulation:** Recycled Rubber Crumb: Incorporate recycled materials like rubber crumb into acoustic insulation designs to absorb sound and reduce noise pollution.
- **Microplastic removal technologies (e.g., nanofillers, bioremediation):** Magnetic Ferrofluids: Develop ferrofluid mixtures that bind to microplastic particles, allowing for their extraction from water using magnetic fields.
- **Acoustophoresis:** Implement acoustophoresis techniques to separate microplastic particles based on their acoustic properties, facilitating their removal from aquatic environments.

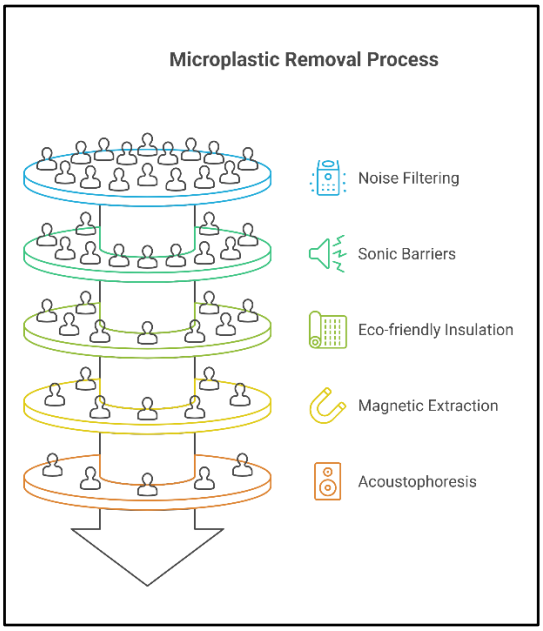

Fig. 4. Microplastic removal process incorporating noise filtering, sonic barriers, eco-friendly insulation, magnetic extraction, and acoustophoresis.

5.2 Integration of acoustic monitoring with pollution detection systems

- **Real-Time Detection:** Combine acoustic monitoring systems with microplastic detection technologies to identify and quantify microplastic concentrations in marine environments.
- **Automated Response:** Develop systems that automatically adjust acoustic parameters or activate removal technologies in response to detected microplastic presence.

5.3 Guidelines for designing underwater equipment with minimal acoustic disruption

Designing underwater equipment to minimize acoustic disruption involves a multifaceted approach. Start by optimizing propeller and hull design to reduce cavitation and turbulence key sources of underwater noise by ensuring smooth hydrodynamic flow and proper propeller alignment with optimized blade geometry. Vibration isolation is critical: machinery should be mounted using elastomeric or dampening mounts to prevent noise transmission into the surrounding water. Anechoic coatings or acoustic-dampening polymers on external surfaces can absorb rather than reflect sound, significantly mitigating radiated noise when properly matched in impedance to the aquatic environment. For research or sensitive operations, adopting classification standards like DNV GL's SILENT notations especially SILENT-A or the more stringent SILENT-R for research vessels provides structured performance criteria for controlling underwater noise emissions. For cutting-edge solutions, acoustic metamaterials such as ultra-thin metal barriers offer promising broadband noise attenuation, particularly in low-frequency ranges. By combining these elements hydrodynamic design, vibration control, acoustic materials, noise-class standards, and advanced metamaterials engineers can significantly reduce the acoustic footprint of underwater equipment, protecting both marine ecosystems and the integrity of acoustic sensing systems.

6. CONCLUSION

Integrated acoustic microplastic models reveal that microplastics, through increased scattering and absorption, significantly alter underwater acoustic propagation, potentially degrading communication and sensor performance. This research demonstrates how such modeling can assist in detecting microplastic contamination and contribute to marine ecosystem preservation through informed engineering strategies. Acoustic monitoring, being non-invasive, continuous, and wide in coverage, is already effective for tracking marine life, environmental noise, and ecosystem health. When combined with AI and acoustic data, it becomes a powerful tool for identifying subtle environmental changes, including microplastic-induced acoustic anomalies, thereby enhancing environmental monitoring capabilities.

Incorporating microplastic effects into acoustic system design supports eco-conscious engineering, ensuring that monitoring tools remain accurate and minimally disruptive, while laying the foundation for sustainable marine infrastructures that account for pollution impacts. Future research should focus on developing real-time monitoring systems through integrated sensor networks such as IoT-enabled acoustic nodes and cameras capable of detecting microplastic concentrations in situ. Additionally, AI-based prediction models leveraging machine learning and deep learning can analyze acoustic and environmental data streams for rapid detection and forecasting. Collaborating with marine biologists will further enable assessment of how altered acoustic environments affect marine species, providing insights into species-specific communication, behavioral patterns, and physiological responses to guide targeted conservation strategies.

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