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Editorial: Advances in marine environmental protection: challenges, solutions and perspectives

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Editorial on the Research Topic
Advances in marine environmental protection: challenges, solutions and perspectives

Introduction

Marine environmental protection has become a pressing global priority. Ocean ecosystems face unprecedented threats from climate change (e.g., warming seas, acidification), biodiversity loss, and pollution (Khan et al., 2024b). These challenges are inherently transboundary—pollutants and their impacts extend beyond national jurisdictions—necessitating shared responsibility and cooperation among nations. Issues such as rising ocean temperatures, plastic pollution, noise pollution, and emerging activities like deep-sea mining are disrupting marine ecosystems (Khan et al., 2024a).

The health of the oceans is directly linked to human well-being and sustainable development, particularly for coastal communities and industries that depend on marine resources. Protecting marine environments is not only an ecological imperative but also essential for food security, climate resilience, and economic livelihoods.

In response to these mounting challenges, significant advances in both technology and policy have been made to safeguard the marine environment. Recent developments range from innovative data-driven tools to landmark international agreements. This Research Topic of *Frontiers in Marine Science*, "*Advances in Marine Environmental Protection: Challenges, Solutions, and Perspectives*," brings together a collection of cutting-edge studies and reviews that highlight these advancements. The contributions cover a wide range of topics, including pollution control, climate change mitigation, legal governance frameworks, and the application of emerging technologies—offering timely insights for policymakers and practitioners seeking to bridge science and policy for ocean sustainability.

Addressing marine pollution challenges

One urgent focal point is marine pollution, particularly the widespread issue of plastic waste. Marine plastic pollution has been recognized as a major obstacle to sustainable ocean development (Khan et al., 2024a). Mismanaged plastic from land enters the ocean through rivers, wind, and runoff, making it a truly global problem. Alarmingly, global plastic production is projected to double within the next decade or two, underscoring the urgent need for bold action and strengthened governance. Several articles in this Research Topic tackle this crisis from different angles.

Plastic pollution, both pervasive and persistent, is the area where policy and technology intersect. A global analysis by (Yu et al.) provides a sobering overview of the current state of plastics in our oceans, from macro-debris to microplastics. Their study reveals widespread contamination, threatening marine ecosystems and human health, and underscores the urgency for coordinated international responses. On the policy front, momentum is building toward a new international treaty on plastics. (Xu et al.) reflects on Japan's participation in the ongoing negotiations for a global plastic pollution treaty under the UN. It notes that Japan has adopted a "conservative but proactive" stance—balancing its domestic framework for managing plastics with a cautious approach to ambitious global targets. Understanding such national positions is crucial for practitioners, as it sheds light on the diplomatic challenges of achieving a strong, legally binding agreement to end plastic pollution. Taken together, these contributions emphasize that tackling marine pollution will require both innovative solutions (e.g., improved waste management technologies and data monitoring) and strengthened policies—from local enforcement to global agreements—to turn the tide on ocean contamination.

Similarly, (Yu and Xu) provided their insights into adopting a human rights-based perspective on Japan's controversial plan to release treated Fukushima nuclear wastewater into the Pacific, this approach argues that nations have extraterritorial obligations to prevent transboundary harm and protect the rights of affected communities. It offers a new discourse for holding states accountable and ensuring that such decisions undergo rigorous scrutiny. Complementing this, (Chen and Xu) examines the international legal framework for environmental impact assessments (EIAs) in the Fukushima water release case, finding that treaties such as the UN Convention on the Law of the Sea (UNCLOS) and other environmental agreements obligate Japan to conduct thorough EIAs throughout the decades-long discharge process. Together, these insights underscore the importance of robust legal tools—ranging from human rights protections to EIA requirements—in managing pollution that crosses borders.

Enhancing sustainability and governance innovations

Beyond pollution, the Research Topic also explores how technological advancements and policy measures can promote broader marine sustainability. Climate change mitigation and adaptation in the ocean domain emerge as key themes. Notably, (Mao et al.) highlights the concept of blue carbon, examining how enhancing the ocean's carbon sink capacity can help meet climate goals. Focusing on Shandong Province in China, their perspective piece illustrates how coastal regions can leverage marine ecosystems (such as seagrass beds and salt marshes) to sequester carbon and contribute to national "dual carbon" targets of peaking emissions and achieving carbon neutrality. They argue for a clear roadmap—investing in blue carbon research, establishing carbon trading markets, and integrating ocean-based mitigation into regional planning—steps that could also serve as guidance for policymakers in other coastal jurisdictions. This example underscores a broader point: marine environmental protection is deeply intertwined with climate action, requiring cross-sectoral strategies that link ocean health with emissions reduction and climate resilience.

Strengthening governance is another key aspect of marine environmental protection, and several contributions examine legal and institutional innovations. Yang analyzes China's experience with Marine Environmental Public Interest Litigation (MEPIL), where prosecutors, agencies, and NGOs bring cases to court to enforce environmental laws. Reviewing 339 cases from 2018 to 2023, the study finds that MEPIL has yielded remarkable results in holding polluters accountable and protecting marine ecosystems. This highlights how empowering legal institutions and civil society can drive better compliance with environmental regulations. At the international level, cooperation is expanding through new agreements. (Wang et al.) discusses that in 2023, nations formally adopted the High Seas Treaty, known as the BBNJ Agreement (Chang et al., 2024), to conserve biodiversity in areas beyond national jurisdiction. This agreement introduces tools such as marine protected areas in the high seas, which require coordination with existing regimes. (Wang and Zhang) discuss how area-based management tools under the International Maritime Organization (such as Particularly Sensitive Sea Areas and MARPOL Special Areas) can align with the BBNJ's new protected zones to improve vessel pollution control on the high seas. Such coordination is vital to prevent gaps or overlaps in governance, ensuring that ships and other ocean uses are regulated consistently across jurisdictional boundaries.

Technology is also emerging as a powerful enabler of marine governance. As highlighted in a review by (Bilawal Khaskheli et al.), advances in monitoring and data management—from satellite remote sensing to autonomous sensors—have revolutionized our ability to understand and manage marine environments. These tools enable more evidence-based decision-making and enhance international collaboration by sharing information in real time. However, they also bring new challenges related to data governance, privacy, and the need to update legal frameworks to accommodate innovations. An illustrative example of harnessing technology for policy is presented by (Wang et al.), who introduce "ChatBBNJ," an AI-powered question-answering system designed to help stakeholders navigate the complex text of the BBNJ Agreement. By combining advanced data engineering with large language

models, Chat BBNJ can swiftly provide users—from diplomats to conservation practitioners—with answers about the treaty's provisions. This not only aids understanding but also helps implement the agreement more effectively by informing decisions with up-to-date knowledge. It exemplifies how digital innovations can bridge the gap between extensive environmental legislation and on-the-ground action.

In summary, the articles in this Research Topic set the stage by highlighting both the daunting challenges and inventive solutions in marine environmental protection. They demonstrate that tackling issues like pollution and climate change requires an integrated approach—blending cutting-edge technology, robust legal frameworks, and inclusive governance. As we delve further into these contributions, several cross-cutting themes emerge: the importance of international cooperation, the role of law in enforcing accountability, and the promise of new technologies to enhance our capacity to protect ocean health. These insights provide a foundation for developing more effective policies and practices, which the subsequent sections of this editorial will explore in greater detail.

Continuing from the opening discussion, the next contributions in this Research Topic highlight both innovative technologies and progressive governance approaches driving marine environmental protection. Several papers focus on strengthening legal and policy frameworks at national and international levels. In particular, two studies examine the recent revision of China's Marine Environmental Protection Law, shedding light on how the updated law enhances institutional coordination, pollution control, and biodiversity conservation (Huang et al.; Liu). These analyses underscore that clearer legal mandates—from stricter liability for polluters to new "Land-and-Sea Coordination" mechanisms—can significantly improve marine governance capacity. Another article focuses on policy incentives for industry compliance, finding that the environmental behavior of maritime manufacturing firms is strongly influenced by the stringency of regional regulations and environmental conditions (Mao and Xu). Interestingly, firms in regions with better marine water quality tended to pursue proactive green innovation, whereas those in more polluted areas adopted defensive strategies, such as obtaining ISO 14001 certification to meet minimum standards. This insight suggests that tailored regulatory approaches—combining strict enforcement with positive incentives—can motivate more ambitious environmental action from the maritime sector.

Cutting-edge research in this Research Topic also addresses emerging challenges and technological solutions in ocean governance. With the international seabed mining regime taking shape, one study reviews Regional Environmental Management Plans under the deep-sea mining framework and identifies gaps, such as limited baseline data and the unclear legal force of these plans (Zhou et al.). The authors recommend stronger scientific data collection and clearer rules to balance resource exploitation with conservation in areas beyond national jurisdiction. Another paper explores the intersection of trade and marine protection, using the Pakistan–China free trade agreement as a case study to illustrate how environmental provisions in trade deals could be strengthened to safeguard marine ecosystems (Khan and Ullah). On the high seas, coordination between new and existing regimes remains critical. For example, the IMO's special areas and the forthcoming BBNJ Agreement's marine protected areas must work in tandem for effective vessel pollution control (Wang and Zhang). Technological innovation features prominently as well: one contribution examines the legal status of electronic bills of lading, highlighting how digitalization in shipping can improve efficiency and reduce paper waste, but also necessitates updates to maritime law to address issues of authenticity and "possession" in electronic form (Sun and He). Likewise, bridging the gap between climate technology and ocean health is a recurring theme. A policy review on "blue carbon" strategies argues that integrating ocean-based carbon sinks into climate policy could bolster both greenhouse gas mitigation and marine habitat protection (Li and Liu). Additionally, as climate change intensifies, courts are increasingly called upon to address environmental harms. A comparative analysis of recent climate litigation (e.g., the Daniel Billy case in Australia) interprets states' due diligence obligations under international law to protect the marine environment from climate impacts, potentially setting important precedents (Liang). Finally, a systematic review of thermal discharges from coastal power plants offers a reminder that traditional pollution issues remain central. It catalogues how waste heat alters marine benthic communities and calls for stricter discharge standards and innovative cooling technologies to mitigate ecological damage (Leng et al.). This set of studies collectively illustrates a dynamic interplay between technology and policy: new tools like digital platforms and data-driven models enhance our ability to manage the oceans, while evolving legal frameworks align these innovations with sustainable development goals. Each insight contributes to a more robust, forward-looking approach to marine environmental protection, from local waters to the high seas.

In coastal ecosystems, managing pollution remains a fundamental challenge. For example, researchers studying a mangrove estuary in Zhanjiang Bay, China, found that sediments near oyster farms accumulate mercury and methylmercury, which raises ecological and health concerns (Zhao et al.). Fortunately, their risk assessment indicated that current mercury exposure from consuming local oysters is low, suggesting that aquaculture can coexist with environmental safety if properly monitored (Zhao et al.). Meanwhile, on a global scale, marine plastic pollution is escalating at an unprecedented rate, infiltrating food chains and even human bloodstreams (Xu). The international community has responded with various regulations, but these efforts remain fragmented. A holistic, unified global plastics treaty is needed to effectively curb this pervasive threat.

Climate change mitigation in the maritime sector has become a priority, particularly in the push to cut greenhouse gas emissions from shipping. Under the International Maritime Organization's roadmap, the global shipping industry is under pressure to drastically reduce its carbon footprint (Hu and Dong). China, for instance, has introduced a series of emission reduction policies for its vast shipping fleet in line with its carbon neutrality ambitions, yielding initial progress but also revealing implementation gaps.

Studies suggest that further measures—combining government regulation with market-based incentives and technological innovation—will be needed to reconcile economic growth with the sector's net-zero targets (Li and Hu).

Coordinating climate action with marine governance frameworks is another emerging theme. One analysis highlights that the UN Convention on the Law of the Sea (UNCLOS) and the UN climate regime have historically operated in silos, leaving a gap in addressing ocean-related climate impacts (Zeng and Wang). Given the ocean's crucial role in regulating the climate, the authors argue for bridging this divide by developing agreements that integrate climate change into ocean law and reinterpret UNCLOS in line with the Paris Agreement commitments. Such legal innovation would help tackle challenges like sea-level rise and ocean acidification more effectively under a unified governance approach.

At the national level, governance innovations are being pursued to better balance the development and protection of marine resources. In China, a novel multi-tiered sea use rights system was introduced in 2023 to allocate offshore space more efficiently and sustainably (Yu and Yue). This approach enables layered uses of marine areas and aims to protect resources while supporting a growing ocean economy. Complementing such spatial management, China is also strengthening its legal framework for marine security and environmental stewardship. A recent analysis of China's maritime legislation underscores efforts to consolidate scattered marine laws into a comprehensive "basic law of the sea" and improve enforcement mechanisms (including data governance and specialized courts) for safeguarding maritime rights (Wang).

Strengthening enforcement and judicial capacity is equally vital for marine environmental protection. An extensive review of over 2,400 marine pollution court cases in China (2019–2023) revealed an encouraging decline in cases over time, suggesting improved compliance and governance outcomes (Liu et al.). However, the study also identified gaps and proposed further judicial reforms, such as establishing specific criminal offenses for serious marine pollution and deploying intelligent trial technologies to expedite cases and standardize legal judgments (Liu et al.). Such measures would strengthen the rule of law's ability to deter violators and ensure consistent enforcement of environmental regulations.

International economic cooperation must also align with environmental objectives. A case in point is the Pakistan–China Free Trade Agreement (FTA), which has spurred rapid trade growth but also unintentionally aggravated marine pollution, overfishing, and habitat loss in both countries (Khan and Xu, 2021). Researchers examining this FTA argue that stronger environmental provisions are needed within trade deals to prevent and mitigate such impacts (Khan and Chang, 2021). They recommend concrete steps, such as adding enforceable environmental clauses to the agreement, creating a joint marine environmental commission, and boosting public participation and domestic environmental laws to safeguard ecosystems amid economic expansion (Khan and Ullah). This highlights the importance of "greening" trade agreements through legal and institutional innovations.

Finally, technological innovation is emerging as a key enabler for sustainable ocean governance and industry practices. One example is the ongoing digital transformation of maritime commerce: the shift from paper-based to electronic bills of lading (eB/Ls). This transition promises greater efficiency and reduced paper use but raises legal questions about how to confer traditional property rights onto digital documents (Sun and He). A comparative legal study outlines three approaches that different jurisdictions are taking to solve this "possession problem" for eB/Ls – ranging from expanding existing definitions of possession to embracing new concepts of electronic control or establishing trusted digital registries (Sun and He). Importantly, the trend is converging toward recognizing "control" of an electronic record as the functional equivalent of possession, paving the way for wider adoption of paperless, secure shipping transactions. By modernizing maritime law in this way, trade can become more efficient without compromising legal certainty, illustrating how innovation and environmental efficiency can go hand in hand.

Conclusion and future directions

As this Research Topic has demonstrated, protecting the marine environment requires a multidimensional approach that integrates scientific advancements, regulatory frameworks, and governance innovations. Several contributions have highlighted that while technology-driven solutions—such as carbon capture for shipping emissions, legal mechanisms for blue carbon conservation, and stricter Arctic shipping regulations—hold great promise, their effectiveness depends on robust policy implementation and international cooperation.

One recurring theme in this Research Topic is the urgent need to enhance legal and institutional mechanisms to ensure that technological progress aligns with sustainability goals. For instance, studies on international fisheries law emphasize that while Sustainable Development Goal 14 (SDG 14) provides a framework for fisheries governance, developing nations face significant hurdles in implementing these principles due to institutional fragmentation and a lack of enforcement capacity. Similarly, research on marine protected areas (MPAs) suggests that, beyond their ecological benefits, they can serve as tools for environmental justice by promoting equitable access to ocean resources and distributing conservation benefits more fairly among communities.

Another key insight from this Research Topic is the increasing role of climate litigation and legal accountability in shaping marine governance. The comparative analysis of *Daniel Billy* et al. *v. Australia* and the COSIS advisory opinion illustrates how international courts are expanding the interpretation of due diligence obligations to address climate-related harms to marine environments. Such legal developments underscore the growing recognition that states must take proactive measures to mitigate climate change impacts, or they risk legal liability.

Beyond governance, the Research Topic also explores emerging risks and the need for stronger safeguards. A systematic review of

thermal and cold discharges from power plants demonstrates how industrial pollution continues to degrade marine ecosystems, urging more stringent environmental impact assessments and mitigation strategies. Additionally, the regulation of unmanned aircraft systems (UAS) in Antarctica reflects broader challenges in governing new maritime technologies, highlighting the necessity for comprehensive and internationally coordinated regulatory frameworks.

Looking ahead, it is clear that marine environmental protection must evolve to keep pace with technological advancements and climate challenges. Strengthening legal frameworks, improving enforcement mechanisms, and enhancing cooperation between states, industries, and scientific communities will be critical in achieving sustainable ocean governance. More research is needed on cross-sectoral strategies that integrate marine conservation, climate mitigation, and economic development to ensure that the oceans remain a viable resource for future generations.

This Research Topic serves as a valuable platform for advancing knowledge and fostering dialogue among policymakers, researchers, and practitioners. As the global community continues to confront the mounting pressures on marine ecosystems, collaborative and interdisciplinary approaches will be essential for achieving meaningful progress.

Author contributions

MK: Conceptualization, Writing – original draft, Formal Analysis, Writing – review & editing, Investigation. Y-CC: Writing – review & editing, Supervision.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Publisher's note

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