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Debris capture during in-water cleaning of ship biofouling

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Ship biofouling interferes with vessel operations and spreads non-indigenous species. While in-water cleaning (IWC) with debris capture is increasingly promoted as a management strategy, key elements remain poorly defined, including which materials must be collected, an acceptable level of capture, and how capture can be quantified. Although the processing efficacy of collected debris can be assessed, because IWC occurs in an open, dynamic system, measurement of overall capture efficiency is not feasible. Thus, ambiguous 'capture' requirements risk inconsistent performance, unnecessary costs, and barriers to innovation. Instead, regulations should emphasize measurable outcomes (e.g., acceptable levels of change in water quality indicators) rather than mandating specific methods. This outcome-based approach would better ensure that IWC supports ship operational efficiency while minimizing biosecurity and environmental contamination risks.

KEYWORDS
ship biofouling, in-water cleaning, capture efficiency, environmental regulations, outcome-based approach

Introduction

The impacts of biofouling on vessel operational efficiency have long been known across the global shipping industry (Townsin, 2003; Schultz, 2007; Pagoropoulos et al., 2018). While operational impacts (e.g., increased corrosion, hydrodynamic drag, and fuel consumption) are obvious due to the occurrence of macrofouling, such as barnacles, tubeworms, and macroalgae (Choi et al., 2024), the initial colonization of microbial biofilms can also result in substantial impacts (Schultz et al., 2011; Farkas et al., 2019). Biofouling-induced inefficiency to fuel consumption also has the knock-on effect of increased greenhouse gas emissions, and has, in turn, drawn considerable attention at both local and international scales (e.g., IMO, 2023a; Liu et al., 2023). Another important impact of ship biofouling is the inadvertent translocation of non-indigenous species between port regions around the world (Hewitt and Campbell, 2010; Ruiz et al., 2015; Davidson et al., 2018; Bailey et al., 2020).

To manage biofouling on submerged ship surfaces, the maritime industry relies on two basic strategies (used separately or in combination): antifouling coatings (AFC) and in-water cleaning (IWC) (GESAMP, 2024). AFC are complex formulations, comprised of polymers as binding agents (i.e., plastics), cosmetic pigments, extenders, and plasticizers. AFC can be further subdivided into: (a) biocidal coatings when employing active ingredients (e.g., cuprous oxide and other inorganic/organic toxic compounds) or (b) non-biocidal coatings that typically limit the adhesion of macrofouling (Dafforn et al., 2011). IWC represents a suite of processes and tools used to remove biofouling on ship surfaces (Scianni and Georgiades, 2019; Tamburri et al., 2021). During IWC, not only are microscopic and/or macroscopic organisms detached, but some amount of abiotic dissolved and particulate material is also released, with amounts dependent on the IWC technology, operator, and AFC (Figure 1).

IWC has evolved in recent decades, transitioning from traditional methods employing divers with handheld brushes and scrapers to more mechanized diver-operated cleaning units or carts. These initial approaches made little or no attempt to collect any of the materials detached from ship hulls and niche areas (e.g., propellers, sea chests, rudders, and thrusters). Modern IWC now includes a variety of proactive (i.e., focused on periodic microfouling or biofilm removal for macrofouling prevention) and reactive (i.e., focused on direct macrofouling removal) systems. Advanced IWC systems can be diver, remotely, or autonomously operated, and commonly perform some type of debris collection, physical separation (e.g., filtration), and, in some cases, additional treatment for the elimination or neutralization of materials of environmental concern (Scianni and Georgiades, 2019; Tamburri et al., 2021; Scianni et al., 2023).

The main driver of ship IWC, both traditional and modern approaches, is the cost savings of reduced fuel consumption. However, with emerging biofouling policies (Santos-Simón et al., 2025), IWC goals have widened to include the minimization of biosecurity and environmental contamination risks (Tamburri et al., 2021, 2022; Scianni et al., 2023). Currently, expectations and claims regarding IWC with 'capture' to mitigate these risks remain vague and inconsistent. Yet biofouling guidance documents and emerging regulations either suggest or require debris capture for some or all IWC operations, without careful consideration of: (a) what specifically needs to be captured, (b) what level of capture efficiency is required/acceptable, or (c) whether capture efficiency can be determined. The purpose of this policy brief is to provide clarity on the term 'capture' as it relates to the IWC of ship biofouling. We also provide recommendations for IWC regulations, approvals, and related environmental policies to help avoid the pitfalls of enacting non-measurable, subjective requirements.

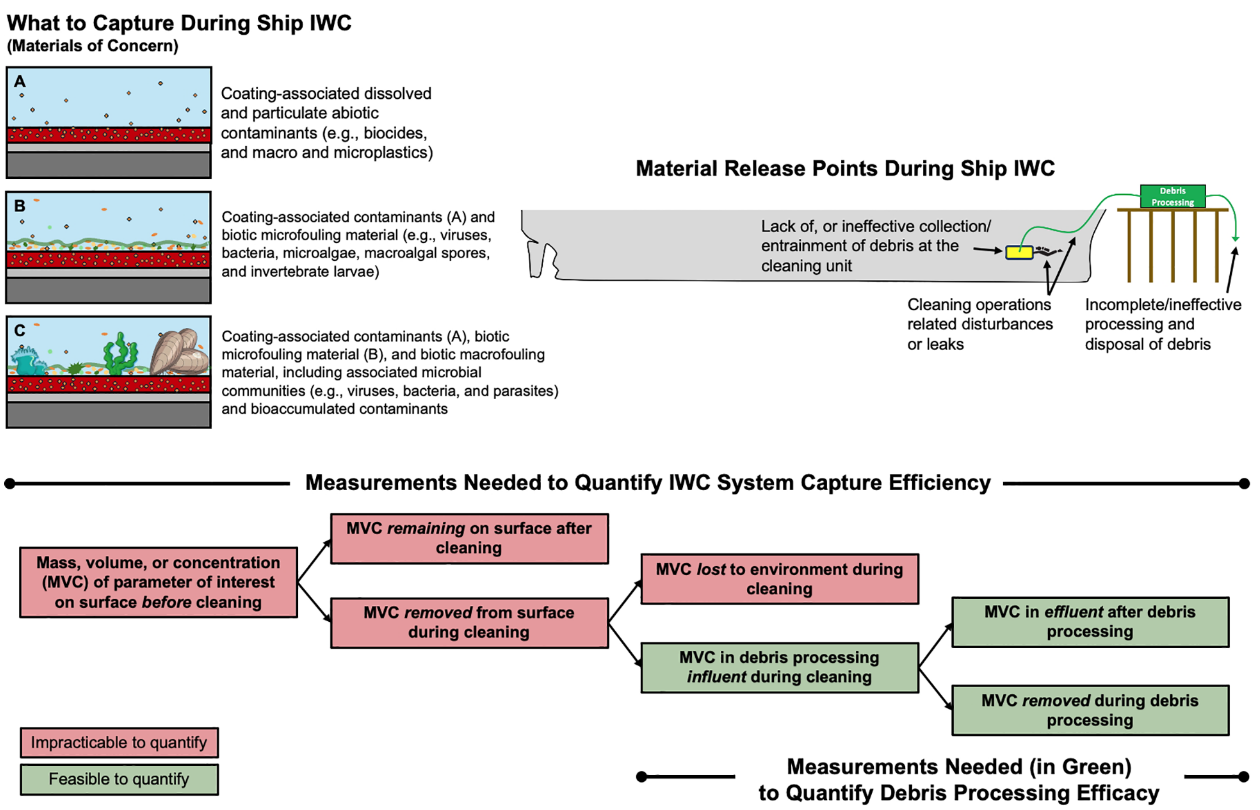

FIGURE 1
The three cumulative categories of material of concern produced by IWC that may require collection and disposal **(A–C)**, examples of release points of possible material of concern during IWC, and the measurements needed to quantify IWC capture efficiency (including what currently cannot be measured in red and can be measured in green).

Debris capture in the context of ship in-water cleaning

The International Maritime Organization (IMO) recently updated its 2011 Guidelines for Biofouling Management on Ships to Minimize the Transfer of Invasive Aquatic Species (IMO, 2023b). These 2023 guidelines provide basic best practice recommendations to minimize biosecurity and environmental risks, and emphasize safe and effective AFC and IWC strategies, as part of a comprehensive ship biofouling management approach. To support the application of the 2023 guidelines, the IMO subsequently developed the Guidance on In-Water Cleaning of Ships' Biofouling (IMO, 2025). This guidance provides suggestions for IWC approvals and operations, including independent testing of IWC systems (e.g., the use of ISO 20679, 2025), minimum IWC performance standards, and the need for demonstrated IWC and AFC compatibility. In both recent IMO documents, there is a clear intent that biofouling management in general, and IWC specifically, should not cause unintended or significant environmental harm. Thus, the capture of debris removed from ship surfaces during IWC is recommended. The IMO (2023b; 2025) defines capture as "the process of containment, collection, and removal of biofouling material and waste substances detached from submerged surfaces during cleaning in water or in dry dock". However, there is no direction on what specifically should be captured. For example, does capture include the collection and disposal of some or all of dissolved and particulate contaminants, microorganisms, and macrofouling organisms? Furthermore, current IMO instruments provide no information on how debris capture should be quantified or on a level of capture performance that would be environmentally acceptable.

Several countries have, or are developing, similar IWC requirements and regulations. For example, in 2024, the US Environmental Protection Agency final national standards of performance for the Vessel Incidental Discharge Act (VIDA) (EPA, 2024) includes requirements for the capture of debris during ship IWC (e.g., "any discharge from IWC without capture of macrofouling is prohibited"). However, VIDA only defines IWC with capture as the "use and operation of a cleaning system for vessel surfaces that is designed to capture and transport coatings and biofouling organisms to an adjacent barge or shore-based facility for collection and processing." Similarly, the 2025 Norway Maritime Authority proposed regulations on the management of ship biofouling (NMA, 2025) include the application of IWC that "shall be carried out using the best available technology at the time," and best available technology is determined in part as "the highest possible capture rate of material released during hull cleaning." However, what material released during IWC needs to be captured, and how to determine the capture rate, are not specified. A consistent and standardized definition of the term 'capture' in the context of IWC, including what specific material(s) need(s) to be captured and an acknowledgment of what can and cannot be measured, is critical for the effective implementation, enforcement, and success of any IWC requirements or approvals, and by extension any biofouling regulations or policies.

Capture in industrial and environmental settings

The concept of 'capture', including associated requirements and methods of quantification, has been examined in numerous disciplines and applied contexts. In the fields of air and water treatment, the term 'capture' refers to the process of extracting specific substances (i.e., contaminants or pollutants) from the media using particular methods or materials to separate, entrain, and/or selectively bind to the target(s). This process allows the remaining air or water to either be released to the environment or to further treatment (e.g., microbial disinfection in drinking water treatment plants). In fully characterized systems, where the amount or concentration of target substances is monitored or known (i.e., can be directly measured) before and after the capture process, rates and efficiencies can be documented in a statistically robust manner. However, while it is not uncommon for the terms 'capture rate' and 'capture efficiency' to be used interchangeably, they are distinct. 'Capture rate' is specific to the amount of target substances successfully collected or eliminated over a particular timeframe (e.g., Ji et al., 2023; Hanson et al., 2025). By contrast, 'capture efficiency' represents the effectiveness of the process in collecting or eliminating substances and is typically expressed as the percent reduction of the amount or concentration of target material (i.e., concentration before capture compared to concentration after capture) (e.g., Sweetman et al., 2018; Zhang and Liu, 2022).

While quantification of capture efficiency can be straightforward in applications with confined and measurable influent and effluent conditions, such as carbon dioxide capture from power plant flue gases (e.g., Obi et al., 2024) and ship ballast water treatment (e.g., Outinen et al., 2024), open systems with unknown and variable conditions are far more challenging. For example, stock assessments and management of many commercial fisheries depend on population estimates from trawl net sampling (e.g., Oyafuso et al., 2022; Latour et al., 2023). These surveys typically assume: (a) all fish in the sampled area are encountered by the trawl and (b) capture vulnerability is known and fish length-dependent (e.g., Dean et al., 2021). However, fish abundance, composition, and size distributions before and after sampling are unknown, and species differ in capture vulnerability due to variations in age, body shape, swimming ability, sensory capacity, and habitat use. Consequently, it is widely recognized that these assumptions are invalid, and the accurate quantification of fish abundance in open ocean systems is not feasible (Mander and Punt, 2013).

Assessing debris capture during in-water cleaning

Similar to fish trawl surveys, ship IWC is an open system with several unknowns, resulting in the impracticality of direct measurement of capture efficiency (or rate) under realistic and predictive operational conditions (Figure 1). Documentation of

IWC capture efficiency would require measures of how much microfouling, macrofouling, and coating material (including dissolved and particulate coating biocides and plastics) was: (a) on the ship surface before cleaning, (b) detached from the ship surface and collected/entrained by the IWC system, (c) detached from the ship surface and not collected/entrained but rather released into the surrounding waters, and (d) remained on the ship surface after cleaning. While the mass and/or volume of the collected material can be estimated from a debris processing stage (e.g., amount of waste gathered and disposed of), there is currently no feasible way to measure the amount of material from a ship's surface that is not collected and enters the environment, beyond measures of change to water quality parameters as a result of IWC (Tamburri et al., 2021; ISO 20679, 2025). Furthermore, while likely a relatively small contributor to environmental release of materials of concern, other IWC operational disturbances beyond the cleaning unit itself (e.g., hoses, tethers, and divers making contact with ship surfaces) should not be ignored until a better understanding of various IWC operations is gained. Thus, given the nature of this open and dynamic system (with diverse materials of concern from ship surfaces continuously being exchanged with surrounding waters even without IWC) and all of the unknowns, it is not currently possible to document overall IWC capture efficiency.

While overall IWC capture efficiency is currently not feasible to quantify, the debris processing efficacy of the material collected/entrained by the cleaning unit can be assessed. Representative samples can be taken and analyzed for the amounts or concentrations of material of concern in the influent and effluent of IWC debris physical separation and/or treatment stages (Tamburri et al., 2021; ISO 20679, 2025). However, a measurable and achievable percentage reduction in these materials during debris processing is not necessarily environmentally protective (Tamburri et al., 2021; Scianni et al., 2023). The debris collected for processing most likely represents only a fraction of the total material detached from ship surfaces (Tamburri et al., 2020; Soon et al., 2024). Moreover, if the material of concern in the influent of IWC debris processing is at a high concentration (which would often be expected; Tamburri et al., 2020), even an aspirational separation/treatment efficacy of 99% could still result in harmful levels being discharged to the environment in the effluent (Tamburri et al., 2021).

There are several recognized abiotic and biotic materials of concern released from ship surfaces during IWC, which may require effective collection, neutralization, and/or disposal (Figures 1A-C) (Georgiades et al., 2021; Tamburri et al., 2021, 2022; Soon et al., 2023; ISO 20678, 2025). Abiotic materials of concern include, but are not limited to: (a) coating-associated *dissolved* inorganic and organic biocides, co- or booster-biocides, and other possible chemical contaminants; (b) coating-associated *particulate* inorganic and organic biocides, co- or booster-biocides, and other possible chemical contaminants; (c) *coating-associated* macro-, micro-, and nanoplastics; and (d) *cleaning unit-associated* macro-, micro-, and nanomaterials (e.g., wearing of cleaning brushes). Biotic material of concern, from a biosecurity and environmental/human health perspective, includes all biofouling organisms, ranging from microbes such as viruses, bacteria, microalgae, macroalgal spores, and invertebrate larvae (within/on biofilms), to intact and fragments of macrofouling organisms and their associated gametes, propagules, microbial communities (e.g., macrofouling-associated viruses, bacteria, and parasites), and bioaccumulated coating biocides found in macrofouling tissues. Fortunately, there are water quality parameters that can be sampled and analyzed to either directly or indirectly identify or estimate the majority of materials of concern during ship IWC (Tamburri et al., 2021; ISO 20678, 2025), and that can provide fundamental insight into IWC capture performance. For example, if there is no statistically significant increase in the measured water quality parameters during IWC, above ambient or background levels, it may be assumed that debris capture is performing appropriately.

Recommendations

Modern IWC systems, designed specifically to reduce environmental impacts, involve a variety of new technologies and continue to evolve and mature. As very few of these systems have undergone comprehensive independent verification testing, there is currently limited information on the best available technologies, how the different approaches function, or their variability in performance (including that of the operator). While the aim of requiring debris capture during IWC is to minimize unintended biosecurity and environmental contamination risks, enacting subjective and unmeasurable requirements may undermine policy and regulatory goals, add unnecessary costs, and stifle innovation that could yield more reliable, efficient, and effective solutions. Some combinations of biofouling extent and AFC may always require effective debris capture during IWC (e.g., heavy hard macrofouling on a biocidal coating), but others may not if they do not result in significant risks. For example, it may be possible for proactive IWC systems to not elevate the release of AFC-associated biocides (Ralston et al., 2022) and plastics during cleaning (e.g., benign removal of only biofilms on a hard foul-release coating). Furthermore, the cleaning unit could also employ an *in situ* treatment (e.g., lasers, heat, or UV radiation) to kill or deactivate microfouling organisms on the surface or after they have been detached to reduce biosecurity risks.

Given that the goal of IWC is to maximize ship operations while minimizing biosecurity and environmental contamination risks, IWC-associated policies, regulations, and approvals should focus on relevant standards or requirements that can be measured, and avoid mandating only one possible approach to meet those standards or requirements. For instance, the safety and efficiency of IWC systems can be evaluated in a scientifically robust manner by assessments of direct and indirect water quality parameters at possible release points of material of concern during cleaning, and comparing them to coinciding background or ambient levels of the same parameters (Tamburri et al., 2021; ISO 20679, 2025). Thus, IWC performance standards could allow environmentally acceptable levels of increase in materials of concern or develop not-to-exceed threshold levels, while remaining agnostic to the means by which the IWC system achieved those requirements (i.e., with or without debris capture).

While measurable water quality performance standards would represent an effective approach to achieving biosecurity and environmental contamination goals, setting arbitrary standards must also be avoided. For example, requiring IWC effluents not to contain particles greater than 10 μm in size (or any size requirement) would be misguided. While this approach may be similar to ballast water management discharge standards (IMO, 2004), it is irrelevant in the context of IWC risks and ignores the release of dissolved biocides (Tamburri et al., 2020), nanoplastics (Tamburri et al., 2022), macroalgal propagules (Sherman et al., 2020), and pathogenic microorganisms (Georgiades et al., 2021). Again, a more appropriate regulatory approach would be to identify acceptable levels of risk for the various materials of concern and set commensurate and feasible limits for concentrations in the receiving water, or require no measurable increases.

Assessing the performance and potential impacts of IWC requires careful consideration. Ship biofouling is a complex, open system influenced by numerous interacting factors that affect all aspects of IWC, including capture effectiveness (Tamburri et al., 2020, 2021; ISO 20679, 2025). While not all possible IWC scenarios and conditions can be evaluated or monitored, system approval testing should be conducted *in situ* on active vessels to minimize assumptions, uncertainties, and biases. Large-tank, *ex situ* testing has been proposed to quantify IWC capture efficiency (Cho et al., 2024), but several significant limitations hinder its representativeness for the diversity of IWC systems and approaches, including the appropriate test tank volumes/dimensions, types and geometries of test surfaces to be cleaned (including niche areas), coating types and ages, biofouling types and extent, and water quality, visibility, and hydrodynamic conditions. Although *ex situ* trials can be a valuable step in technology research and development, representative and predictive *in situ* testing is essential for meaningful assessments of IWC performance and possible impacts (IMO, 2025).

Finally, two additional IWC capture issues are currently being overlooked but are key to the success of related environmental regulations. First, when IWC includes some form of debris capture, all gathered material must be handled and disposed of in an environmentally acceptable manner. Second, the IWC of ship niche areas is challenging and inconsistently implemented, if at all. Capture of materials of concern released from surfaces during complex niche area cleaning is also more difficult than when cleaning large, relatively flat hull areas, and is currently either not attempted or crudely performed. Given that niche areas are more likely to be heavily fouled and hence, a higher biosecurity risk than hull areas (Coutts et al., 2003; Frey et al., 2014), inadequate collection of debris may carry significant environmental consequences.

Conclusions

To be effective, a capture requirement must specify target materials and their necessary capture efficiency. However, in the context of IWC of ship biofouling, direct measurement of overall capture efficiency is not feasible. This 'capture dilemma' presents challenges that must be acknowledged by all stakeholders, including regulators and IWC service providers. Although direct measurement of overall IWC capture efficiency is impractical, the efficacy of debris processing can be assessed and should be documented for any IWC system employing some form of debris collection. Debris processing efficacy, however, *must not* be conflated with overall IWC capture efficiency. Instead, changes in direct and indirect water quality indicators should be evaluated by appropriately sampling and analyzing background waters and waters at all release points for all IWC systems (with or without capture) during normal cleaning operations. Such data can facilitate statistical detection of significant releases of material resulting from an IWC event, which produce increases above background or the exceedance of prescribed thresholds.

IWC of ship biofouling has the potential to deliver mutual benefits to the maritime industry and the environment—provided that individual systems can be shown to be both safe and effective. For IWC policies, regulations, and approvals to succeed, they should prioritize demonstrating no, or only acceptable levels of, environmental harm rather than mandating specific risk-mitigation methods that may or may not actually be effective or needed. The successful capture and disposal of debris is a viable risk-mitigation method, but it is only one potential approach to achieving safe and effective IWC.

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References

Bailey, S. A., Brown, L., Campbell, M. L., Canning-Clode, J., Carlton, J. T., Castro, N., et al. (2020). Trends in the detection of aquatic non-indigenous species across global marine, estuarine and freshwater ecosystems: A 50-year perspective. *Divers. Distrib.* 26, 1780–1797. doi: 10.1111/ddi.13167

Cho, Y., Kim, S.-J., Kim, M.-S., Yang, J., and Choi, J. (2024). Development of capture efficacy test method for in-water cleaning system using artificial barnacles. *Front. Mar. Sci.* 11. doi: 10.3389/fmars.2024.1404472

Choi, W. S., Min, G. S., Han, S. S., Yun, H. C., Terziev, M., Dai, S., et al. (2024). Resistance and speed penalty of a naval ship with hull roughness. *Ocean Eng.* 312, 119058. doi: 10.1016/j.oceaneng.2024.119058

Coutts, A. D. M., Moore, K. M., and Hewitt, C. L. (2003). Ships' sea-chests: an overlooked transfer mechanism for non-indigenous marine species? *Mar. Poll. Bull.* 46, 1504–1515. doi: 10.1016/S0025-326X(03)00292-3

Dafforn, K. A., Lewis, J. A., and Johnston, E. L. (2011). Antifouling strategies: history and regulation, ecological impacts and mitigation. *Mar. pollut. Bull.* 62, 453–465. doi: 10.1016/j.marpolbul.2011.01.012

Davidson, I. C., Scianni, C., Minton, M. S., and Ruiz, G. M. (2018). A history of ship specialization and consequences for marine invasions, management, and policy. *J. Appl. Ecol.* 55, 1799–1811. doi: 10.1111/1365-2664.13114

Dean, M. J., Hoffman, W. S., Buchan, N. C., Cadrin, S. X., and Grabowski, J. H. (2021). The influence of trawl efficiency assumptions on survey-based population metrics. *ICES J. Mar. Sci.* 78, 2858–2874. doi: 10.1093/icesjms/fsab164

EPA (US Environmental Protection Agency) (2024). *Vessel Incidental Discharge National Standards of Performance* (US Federal Register). Available online at: www.federalregister.gov/documents/2024/10/09/2024-22013/vessel-incidental-discharge-national-standards-of-performance (Accessed November 2024).

Farkas, A., Degiuli, N., and Martić, I. (2019). Impact of biofilm on the resistance characteristics and nominal wake. Proceedings of the Institution of Mechanical Engineers, Part M. *J. Eng. Mar. Env.* 234, 59–75. doi: 10.1177/1475090219862897

Frey, M. A., Simard, N., Robichaud, D. D., Martin, J. L., and Therriault, T. W. (2014). Fouling around: vessel sea-chests as a vector for the introduction and spread of aquatic invasive species. *Manage. Biol. Invsion* 5, 21. doi: 10.3391/mbi.2014.5.1.02

Georgiades, E., Scianni, C., Davidson, I., Tamburri, M. N., First, M. R., Ruiz, G., et al. (2021). The role of vessel biofouling in the translocation of marine pathogens: management considerations and challenges. *Front. Mar. Sci.* 8. doi: 10.3389/fmars.2021.660125

GESAMP (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UNEP/ISA/UNDP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection) (2024). *Marine Biofouling: Non-Indigenous Species and Management Across Sectors. Rep. Stud. GESAMP No. 114.* Available online at: www.gesamp.org/publications/marine-biofouling-non-indigenous-species-and-management-across-sectors (Accessed August 2024).

Hanson, E., Nwakile, C., and Hammed, V. O. (2025). Carbon capture, utilization, and storage (CCUS) technologies: evaluating the effectiveness of advanced CCUS solutions for reducing CO_2 emissions. *Results Surf. Interfaces* 18, 100381. doi: 10.1016/j.rsurfi.2024.100381

Hewitt, C. L., and Campbell, M. L. (2010). *The relative contribution of vectors to the introduction and translocation of invasive marine species* (Canberra ACT: Commissioned by the Department of Agriculture, Fisheries and Forestry). Available online at: www.marinepests.gov.au/sites/default/files/Documents/relative-contribution-vectors-introduction-translocation-invasive-marine-species.doc&ved=2ahUKEwisoprQuZePAxWWKFkFHcq-IrUQFnoECBoQAQ&usg=AOvVaw1LHfoIuLkR3f7yFaSvmIqp (Accessed July 2025).

IMO (International Maritime Organization) (2004). *International Convention for the Control and Management of Ships' Ballast Water and Sediments.* Available online at: www.imo.org/en/ourwork/environment/pages/bwmconventionandguidelines.aspx (Accessed July 2025).

IMO (International Maritime Organization) (2023a). *Strategy on Reduction of GHG Emissions from Ships* (London). Available online at: www.imo.org/en/ourwork/environment/pages/2023-imo-strategy-on-reduction-of-ghg-emissions-from-ships.aspx (Accessed July 2025).

IMO (International Maritime Organization) (2023b). *Guidelines for the Control and Management of Ships' Biofouling to Minimize the Transfer of Invasive Aquatic Species* (London). Available online at: www.cdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MEPCDocuments/MEPC.378%2880%29.pdf (Accessed September 2023).

IMO (International Maritime Organization) (2025). *Guidance on In-Water Cleaning of Ships' Biofouling* (London). Available online at: www.cdn.imo.org/localresources/en/OurWork/Environment/Documents/Biofouling%20pages/MEPC.1-Circ.918%20-%20Guidance%20On%20In-Water%20Cleaning%20Of%20Ships%27%20Biofouling%20(Secretariat).pdf (Accessed May 2025).

ISO (International Organization for Standards) (2025). *Testing of ship biofouling in-water cleaning systems.* Available online at: www.iso.org/standard/86393.html (Accessed January 2025).

Ji, X., Huang, J., Teng, L., Li, S., Cai, W., Chen, Z., et al. (2023). Advances in particulate matter filtration: Materials, performance, and application. *Green. Energy Environ.* 8, 673–697. doi: 10.1016/j.gee.2022.03.012

Latour, R. J., Gartland, J., and Bonzek, C. F. (2023). Design and redesign of a bottom trawl survey in Chesapeake Bay, USA. *Front. Mar. Sci.* 10. doi: 10.3389/fmars.2023.1217792

Liu, S., Kee, Y. H., Shang, B., and Papanikolaou, A. (2023). Assessment of the economic, environmental and safety impact of biofouling on a ship's hull and propeller. *Ocean Eng.* 285, 115481. doi: 10.1016/j.oceaneng.2023.115481.{it}

Mander, M. N., and Punt, A. (2013). A review of integrated analysis in fisheries stock assessment. *Fish. Res.* 142, 61–74. doi: 10.1016/j.fishres.2012.07.025

NMA (Norwegian Maritime Authority) (2025). *Proposed regulations on the management of hull biofouling.* Available online at: www.sdir.no/contentassets/9acc75d5a477489785df7de2afdd850a/proposed-regulations-of-on-the-management-of-hull-biofouling-.pdf (Accessed June 2025).

Obi, D., Onyekuru, S., and Orga, A. (2024). Review of recent process developments in the field of carbon dioxide (CO_2) capture from power plants flue gases and the future perspectives. *Int. J. Sustain. Energy* 43. doi: 10.1080/14786451.2024.2317137

Outinen, O., Bailey, S. A., Casas-Monroy, O., Delacroix, S., Gorgula, S., Griniene, E., et al. (2024). Biological testing of ships' ballast water indicates challenges for the implementation of the Ballast Water Management Convention. *Front. Mar. Sci.* 11. doi: 10.3389/fmars.2024.1334286

Oyafuso, Z. S., Barnett, L. A. K., Siple, M. C., and Kotwicki, S. (2022). *A flexible approach to optimizing the Gulf of Alaska groundfish bottom trawl survey design for abundance estimation* (Washington, DC: Alaska Fisheries Science Center, Resource Assessment and Conservation Engineering Division, NOAA technical memorandum NMFS-AFSC), 434. doi: 10.25923/g5zd-be29

Pagoropoulos, A., Kjaer, L. L., and Dong, Y. (2018). Economic and environmental impact trade-offs related to in-water hull cleanings of merchant vessels. *J. Ind. Ecol.* 22, 916–929. doi: 10.1111/jiec.12627

Ralston, E., Gardner, H., Hunsucker, K. Z., and Swain, G. (2022). The effect of grooming on five commercial antifouling coatings. *Front. Mar. Sci.* 9. doi: 10.3389/fmars.2022.836555

Ruiz, G. M., Fofonoff, P. W., Steves, B. P., and Carlton, J. T. (2015). Invasion history and vector dynamics in coastal marine ecosystems: a North American perspective. *Aquat. Ecosyst. Health Manage.* 18, 299–311. doi: 10.1080/14634988.2015.1027534

Santos-Simón, M., de la Yedra, A. F. G., Ortiz-Zarragoitia, M., and Marchini, A. (2025). Past, present and (possible) future of biofouling regulatory instruments within the international marine environmental protection framework. *Environ. Sci. Eur.* 37, 127. doi: 10.1186/s12302-025-01178-7

Schultz, M. P. (2007). Effects of coating roughness and biofouling on ship resistance and powering. *Biofouling* 23, 331–341. doi: 10.1080/08927010701461974

Schultz, M. P., Bendick, J. A., Holm, E. R., and Hertel, W. M. (2011). Economic impact of biofouling on a naval surface ship. *Biofouling* 27, 87–98. doi: 10.1080/08927014.2010.542809

Scianni, C., and Georgiades, E. (2019). Vessel in-water cleaning or treatment: identification of environmental risks and science needs for evidence-based decision making. *Front. Mar. Sci.* 6. doi: 10.3389/fmars.2019.00467

Scianni, C., Georgiades, E., Mihaylova, R., and Tamburri, M. N. (2023). Balancing the consequences of in-water cleaning of biofouling to improve ship efficiency and reduce biosecurity risk. *Front. Mar. Sci.* 10. doi: 10.3389/fmars.2023.1239723

Sherman, C. D. H., Jennings, G., and Miller, A. D. (2020). *Assessment of reproductive propagule size for biofouling risk groups* (Canberra: Department of Agriculture, Water and the Environment). Available online at: www.agriculture.gov.au/sites/default/files/documents/assessment-of-reproductive-propagule-size-for-biofouling-risk-groups.pdf (Accessed July 2025).

Soon, Z. Y., Kim, T., Jung, J. H., and Kim, M. (2023). Metals and suspended solids in the effluents from in-water hull cleaning by remotely operated vehicle (ROV): Concentrations and release rates into the marine environment. *J. Hazard. Mater.* 460, 132456. doi: 10.1016/j.jhazmat.2023.132456

Soon, Z. Y., Tamburri, M. N., Kim, T., and Kim, M. (2024). Estimating total microplastic loads to the marine environment as a result of ship biofouling in-water cleaning. *Front. Mar. Sci.* 11. doi: 10.3389/fmars.2024.1502000

Sweetman, M. J., Sebben, D., Noll, B. D., Wang, W. H., May, S., Mebberson, N., et al. (2018). A rapid technique to determine performance and efficiency of activated carbon water filters. *Water Supply* 18, 371–382. doi: 10.2166/ws.2017.123

Tamburri, M. N., Davidson, I. C., First, M. R., Scianni, C., Newcomer, K., Inglis, G. J., et al. (2020). In-water cleaning and capture to remove ship biofouling: an initial evaluation of efficacy and environmental safety. *Front. Mar. Sci.* 7. doi: 10.3389/fmars.2020.00437

Tamburri, M. N., Georgiades, E. T., Scianni, C., First, M. R., Ruiz, G. M., and Junemann, C. E. (2021). Technical considerations for development of policy and approvals for in-water cleaning of ship biofouling. *Front. Mar. Sci.* 8. doi: 10.3389/fmars.2021.804766

Tamburri, M. N., Soon, Z. Y., Scianni, C., Øpstad, C. L., Oxtoby, N. S., Doran, S., et al. (2022). Understanding the potential release of microplastics from coatings used on commercial ships. *Front. Mar. Sci.* 9. doi: 10.3389/fmars.2022.1074654

Townsin, R. L. (2003). The ship hull fouling penalty. *Biofouling* 19, 9–15. doi: 10.1080/0892701031000088535

Zhang, X., and Liu, J. (2022). Simplified model for the calculation of the particle capture process in air filter media. *Chem. Eng. Sci.* 249, 117358. doi: 10.1016/j.ces.2021.117358