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# Understanding the potential release of microplastics from coatings used on commercial ships

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Microplastic pollution in the ocean is a critical, global environmental concern. Although believed to be a comparatively small contributor, the paints applied to commercial ships have been identified as a source of microplastics because polymers are used as binding agents in all anticorrosive and antifouling marine coatings. Furthermore, the release of microplastics from coatings may be amplified by in-water cleaning operations to remove biofouling. A comprehensive, detailed assessment and review of the array of commercial ships' coatings, specifically characteristics, behavior, and fate over time, has not been conducted in the context of ocean microplastic pollution. This Policy Brief identifies gaps and proposes actions to better understand the fate of released particles with the goal to inform appropriate and effective solutions.

## KEYWORDS

ocean plastics, marine coatings, polymers, ship anti-fouling systems, microplastics

## Introduction

Plastics (i.e., solid materials made from polymers) have become indispensable in our daily lives, owing to their adaptability, versatility, and relatively low cost. In the late 1960s, due to their widespread use around the world, plastics were first reported as marine pollutants with the discovery of polymers in the remains of birds, specifically, Laysan albatrosses (*Phoebastria immutabilis*) (Kenyon and Kridler, 1969). Instead of harmlessly degrading, it was discovered that many plastics often fragment into smaller, and very long-lived, particles in the ocean (Carpenter and Smith, 1972).

Recently, there has been intense global interest in plastic pollution in the oceans, particularly regarding the “garbage patch” of marine debris in the North Pacific Ocean (e.g., [Lebreton et al., 2018](#)). On a smaller scale, high concentrations of microplastics have also been found within the water column in various locations (e.g., [Coyle et al., 2020](#)). An estimated 14.4 M tons of microplastics have sunk to the ocean floor since polymers were first used ([Barrett et al., 2020](#)). Additionally, microplastics physical and chemical properties may allow them to adsorb toxic chemicals (e.g., heavy metals and organic contaminants) from the environment ([Holmes et al., 2012](#); [Godoy et al., 2019](#)). If consumed by marine organisms, toxins can be introduced into trophic networks and food webs ([Verla et al., 2019](#); [Costa et al., 2020](#); [Zhu et al., 2021](#)).

At a coarse level, microplastics can be binned into primary microplastics (directly released into marine systems as small particulates) and secondary microplastics (fragments from the degradation of larger plastic items). The sources of ocean microplastics can be further classified into seven major categories ([Boucher and Friot, 2017](#)):

- plastic pellets (from manufacturing, transport, and recycling);
- synthetic textiles (abrasion during laundry);
- tires (abrasion while driving);
- road markings (weathering and abrasion by vehicles);
- marine ship/boat coatings (weathering and incidents during application, maintenance, and disposal);
- personal care products (pouring during product use); and
- city dust (weathering, abrasion, and/or pouring of building coatings, synthetic soles of footwear, synthetic cooking utensils, detergents, artificial turfs, etc.).

Multiple studies have attempted to estimate the contribution of these different sources of microplastics towards overall ocean pollution (e.g., [Pruter, 1987](#); [Andrady, 2017](#); [Su et al., 2022](#)), but uncertainties remain in both the many possible sources and each of their relative impacts.

Although terrestrial sources are considered the major inputs of plastic pollution, direct ocean-based sources, such as plastics released during commercial shipping activities, aquaculture operations, and fishing, are also recognized contributors ([Peng et al., 2022](#)). A review by the International Maritime Organization (IMO) concluded that commercial shipping operations may be a notable source of marine plastic pollution through the release of waste, marine coatings, and gray water (e.g., discharges from galleys, sinks, shower, laundries) ([GESAMP, 2021](#)). For example, cruise ships’ gray water can contain 2,000 to 50,000 microplastic particles per liter ([Mikkola, 2020](#)). Further, several studies describe debris collected on beaches as likely connected directly to shipping activities (e.g., [Santos et al., 2005](#); [Smith et al., 2018](#); [Ryan et al., 2019](#)). Indeed,

preventative regulations promulgated by the IMO (e.g., Annex V of MARPOL) are intended to improve ship waste (including plastics) management systems.

Recently, attention has turned to the potential for release of microplastics from commercial ships’ coatings. Herein, “marine coatings” means any coating or coating system (a.k.a. paint) that is used on the outside surfaces of ships (above or below the waterline), including antifouling coatings, anticorrosion coatings, cosmetic finishes, and tie-coats (used to join successive coating layers together). High performing biocidal and non-biocidal antifouling coatings are essential in minimizing the transfer of non-indigenous species (NIS) in biofouling, reducing the need for underwater cleaning of biofouling, and reducing ship drag and fuel consumption (thereby decreasing operational costs and greenhouse gas emissions). However, because marine coatings use polymers as binding agents, there is also a potential for the release of microplastics (e.g., [Gaylarde et al., 2021](#); [Turner, 2021](#)).

The liberation of microplastics associated with marine coatings (during application, throughout the coating’s approximate five-year service life, and during removal and disposal) has been suggested to be an important contributor to ocean plastic pollution (e.g., [Dibke et al., 2021](#)). For example, [Boucher and Friot \(2017\)](#) predict that perhaps 3.7% (~55,000 tons/year) of the 1.5 M tons/year of primary ocean microplastics are from ship and yacht coatings. However, given the limited available data, more comprehensive and careful estimates are critically needed to fully understand the scope and scale of microplastics release from ships coatings and to identify possible solutions.

The main release of microplastics associated with a ship’s coating is thought to be a direct result of ultraviolet (UV) radiation, heat, microbial activity, and mechanical stress from wave and wind energy, all of which are known to degrade marine coatings ([Min et al., 2020](#)). These processes may be further exacerbated and accelerated by in-water cleaning (IWC) of biofouling (the physical removal of biofilms, macrofouling, or both from submerged ship surfaces) ([Scianni and Georgiades, 2019](#); [Tamburri et al., 2020](#); [Tamburri et al., 2021](#)).

While estimates of microplastic release from ships’ coatings have raised environmental concerns (e.g., conveying toxicity to non-targeted organisms and biocide leaching from microplastics), this complicated issue has yet to be thoroughly investigated. Many facets of this issue are largely unknown, including:

- the concentrations and types of polymers used as binding agents in the many different marine coatings currently in use;
- the variable behavior and fate of the different polymers in different coatings over time; and
- the concentrations, biological availability, and environmental impacts of these diverse polymers (and their by-products).

This Policy Brief discusses relevant existing and emerging regulations, proposes standardized terminology, and describes knowledge gaps that need to be addressed before meaningful steps can be taken to minimize the potentially harmful release of microplastics from commercial ship coatings.

## Existing policy

The overarching and global instrument addressing the release of plastics from the shipping industry is the International Convention for the Prevention of Pollution from Ships, which was adopted in 1973 by the IMO and modified in 1978 (MARPOL 73/78; IMO, 1978). Annexes I and II entered into force in 1983. Annex V (Regulations for the Prevention of Pollution by Garbage from Ships) took the step to ban the discharge of all plastic from ships. It entered into force in 1988 and is nearly universally applied: at present, 155 contracting States representing 98.49% of the world's shipping tonnage have ratified it (IMO, 2022b). More broadly, the Convention on the Prevention of Marine Pollution by Dumping of Wastes and other Matter, 1972 (London Convention) prevented dumping at sea. It was modernized by the 1996 Protocol (London Protocol), which entered into force in 2006. To specifically address the fraction of marine plastic litter that emanates from ships, the IMO developed an Action Plan in 2018 (MEPC.310[73]; IMO, 2018).

Microplastic regulations at international, national, regional (e.g., state or territory), and local levels are relatively numerous, but they are narrowly targeted toward individual sources, such as microbeads in cosmetics and other personal care products (e.g., U.S. Microbead-Free Waters Act of 2015, H.R. 1321). Currently, no policy or regulation exists that addresses the release of microplastics from maritime shipping activities. One proposal that would directly affect the use of microplastics in coatings is the European Union's Registration, Evaluation, Authorization, and Restriction of Chemicals Act (REACH). The legislation would restrict the intentional addition of microplastic particles in everyday products, including paints and coatings, although the official proposal has been delayed and is not yet in force (Faber et al., 2021; ECHA, 2022). However, given the global

nature of commercial shipping, effective regulations will be challenging unless implemented at an international level. Furthermore, regulations to limit/prohibit the use of polymers in marine coatings should only be considered after there is a much more holistic understanding of potential environmental concerns.

## Terminology

Microplastics were first described by Thompson et al. (2004), and they subsequently have been categorized by different organizations into groups based on size. At present, no size distribution scheme is used in a globally consistent way (ISO 2020). For comparison across research studies and for clarity as regulations are considered and implemented, a universally accepted definition is critical. We propose combining two of the most-often used classifications, GESAMP (2019) and ISO (2020) (Table 1). In this manner, marine plastic "litter" is binned into various size classes (Table 1), with microplastics from ships' coatings defined as particles  $\geq 1 \mu\text{m}$  and  $< 5 \text{ mm}$ .

## Gaps and recommendations

While no existing regulations address microplastic release from ship coatings, growing awareness of this issue has begun to stimulate interest in the possible development of future guidelines, best-practices, and policies. However, the success of any approach to minimize the impacts of microplastic release from ship coatings is dependent on sound, scientific understanding of the:

- variability in composition of marine coatings;
- behavior and fate of polymers in different coatings, in different environments, over the lifetime of the coatings (e.g., mechanisms of possible release, the chemical and physical properties, movement, and degradation); and
- the concentrations, biological availability, and environmental impacts of any released microplastics and their by-products.

TABLE 1 Proposed classification of ocean plastics with respect to marine coatings, which combine definitions in ISO/TR 21960:2020 and GESAMP 2019.

Broad Size Classes	Size Sub-Categories	Size Ranges (in maximum dimension)
Macroplastic (MAP) ( $\geq 5 \text{ mm}$ )	Mega scale	$\geq 1,000 \text{ mm}$
	Macro scale	$\geq 25 \text{ mm}$ and $< 1,000 \text{ mm}$
	Meso scale	$\geq 5 \text{ mm}$ and $< 25 \text{ mm}$
Microplastic ( $\geq 1 \mu\text{m}$ and $< 5 \text{ mm}$ )	Large Micro scale	$\geq 1 \text{ mm}$ and $< 5 \text{ mm}$
	Micro scale	$\geq 1 \mu\text{m}$ and $< 1 \text{ mm}$
Nanoplastic ( $< 1 \mu\text{m}$ )	Nano scale	$< 1 \mu\text{m}$

This section discusses the main uncertainties and proposes actions to address them.

*Composition* – Polymer binders are the primary contributor to most of the functional performance of coatings and the main potential source of plastic materials (OECD, 2009). Minor contents of other organic polymers are used in most coatings as functional additive ingredients. The total percentage of polymer binders can vary widely, depending on the type of coating and the specific performance requirements. This range is found because coatings' functional features—such as barrier properties, protection, gloss, hardness, weathering resistance – are all influenced by the amount and type of binder used. Indeed, the binder content (percentage of the total solid mass) typically varies from 10-90% (~40% for many commonly used coatings) (Tasche et al., 2020). However, it must be noted that the polymers used in coatings may range from low-molecular weight organic oligomers to high-molecular weight and non-degradable polymers, and mixing different polymers within a single coating is not uncommon (Tasche et al., 2020). A further complicating factor is that the relative concentration of polymers in any specific coating type will often change throughout its service life (i.e., as the coating interacts with the environment over time, including the normal leaching of biocides and pigments) (Kiil et al., 2001; Yebra et al., 2004; Yebra et al., 2006).

Plastic bottles and bags, which often end up as ocean plastic pollution, are nearly 100% polymers, with a relatively small amount of non-polymeric additives (e.g., Siddiqui et al., 2008; Hansen et al., 2013). Conversely, standard coating particles are irregular composite materials containing a greater proportion of additives and, consequently, tend to be more brittle, angular, opaque, dense, heterogeneous, and layered than other microplastics of equivalent dimensions (Turner, 2021). All of this variability begs the question: How much polymer is needed for a particle to be considered a “microplastic”? We propose to define ships' microplastics as any particle containing  $\geq 10\%$  polymer content, with the entire mass of the particle considered a microplastic. This conservative approach is based on the lower end of polymer content found in marine coatings and is, therefore, environmentally protective.

*Behavior and fate of microparticles* – Marine coatings vary widely in their intended function and lifetime, and they are designed to fit individual needs and performance criteria (Turner, 2021). Additives such as metal-containing and organic biocides, pigments, and corrosion inhibitors are typically included in specific marine coating applications (Singh and Turner, 2009; Gade et al., 2012; Soroldoni et al., 2017). Not surprisingly, these components can increase environmental concerns, including producing potentially toxic conditions for aquatic organisms (Soon et al., 2021).

Many coatings have weathering resistance or corrosion protection as their primary function. Here, the binders used

are specifically chosen for their durability and resilience to chemical, physical, or mechanical degradation. Alternatively, “self-polishing” antifouling coatings are specifically designed to be consumed (sloughed off or removed) during their service life. This action occurs through controlled chemical processes such as hydrolysis or ion exchange, thereby providing optimal resistance to biofouling on the ship's submerged surfaces (e.g., Bressy et al., 2009; Kwon et al., 2020). Through self-polishing mechanisms, these polymers are generally understood to be released as hydrophilic, water-soluble polymers rather than released as solid, particulate materials (Zhang and Chiao, 2015). Such marine coating systems themselves could still be a source of microplastics (e.g., when the coating is damaged or abraded, including on ice-breaking vessels; Leistenschneider et al., 2021).

Marine coatings on the outside hulls of commercial ships are generally applied as part of a coating system or scheme. They often comprise several layers of topcoat (e.g., antifouling paint or cosmetic finish) over an anticorrosive coating, “tie-coats” (which act as bridges between layers), or both. The diversity of chemistries and properties of binders used in a coating will ultimately be an important factor in determining its risk of releasing microplastics throughout its in-service period (i.e., the typical five-year interval between successive dry dockings). We recommend a comprehensive evaluation of the intended use of commonly used coatings and their inherent features, combined with situations/scenarios that can cause particles to be released. We also recommend empirical assessments of marine coating associate particle movement (once released from a ship), and particle physical and chemical changes over time and under diverse environmental conditions.

*Concentrations, biological availability, and environmental impacts* – Microplastic particles can be released from ships to the environment through five scenarios, during: (a) coating application, (b) in-service use, (c) IWC of biofouling, (d) routine ship maintenance (e.g., submerged surface and equipment inspections and testing; replacing anodes; pipe and valve maintenance, repair, replacement and blanking; repair and replacing suction and vent grates), and (e) end-of-life (i.e., coating removal and disposal or ship decommissioning/scraping) (Figure 1).

Four of the five scenarios (excluding in-service wear) can be managed or controlled because human involvement is inherent in their operations. In each scenario, preventive measures (e.g., using closed systems, collecting debris, or applying specialized techniques) can be implemented to mitigate or avoid/minimize releasing coating particles. Certainly, these activities will be most effective if best practices are universally identified and adopted (e.g., EU IPPC legislation covering shipyards).

In-water cleaning systems that: (a) minimize the release of coating particles during cleaning, (b) effectively capture

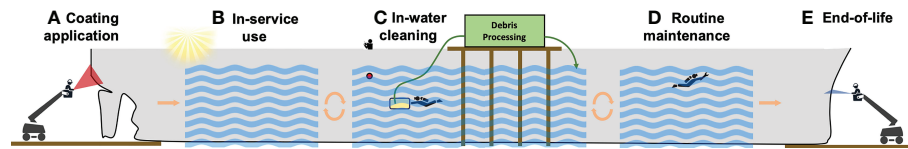


FIGURE 1

Representation (not to scale) of the five scenarios for microplastic release from a ship's coating throughout its typical five-year, in-service period: (A) shipyard/drydocking application; (B) in-service use, including normal wear and tear; (C) in-water cleaning of biofouling on submerged ship surfaces, which can be proactive (using remotely operated vehicles [red circle]) or reactive (using diver- or remotely operated cleaning [yellow rectangle]); (D) routine/required ship and coating maintenance, such as replacing anodes or maintaining pipes and valves; and (E) shipyard/drydocking end-of-life coating system removal and disposal and/or surface preparation for re-coating.

particulate material removed from ships surfaces, or (c) both, will limit the amount of microplastics emitted during operations (e.g., Scianni and Georgiades, 2019; Tamburri et al., 2021). The IWC system itself may also be a source of microplastics if, for example, cleaning brushes wear and produce microplastics. However, not all IWC use plastic brushes and, when they do, the amount of brush wear/loss can be quantified (e.g., before- and after- measures). Brush-associated plastics can also be captured and disposed of, like other cleaning debris. Regardless, if the use and frequency of IWC increases across the global fleet of commercial ships, ensuring effective capture and disposal of coating particles, and cleaning debris more broadly, will become critical. It should be noted that the frequency of IWC will also be influenced by the choice of coating system and the ship's operational profile and environmental conditions (although some ships are not cleaned during their specified in-service period).

During the marine coating's normal in-service use stage, there is little direct, targeted human influence on the coating. The majority of particles release will take place through adventitious processes, such as weathering, corrosion, degradation, erosion or mechanical damages from unintended operational incidents (e.g., groundings, fender damage, anchor chain damage, or collisions). Microplastic release from such processes is generally relevant to coatings that are directly exposed to the environment during the in-service use stage (generally topcoats), as other coatings that are part of a coating system (e.g., primers, tie-coats, middle coats) will not be exposed to natural conditions that may cause particle release. Release from mechanical damage during the use stage is more likely to influence all coating types but typically in relatively small affected areas.

It is expected that there is a significant difference in the morphology of particles formed during the in-service stage, depending on their mode of generation. Particles from the normal wearing processes might be expected to be significantly

smaller in size and of a relatively uniform nature. It is also possible that the binder polymers may be partially degraded from such processes, so that further degradation and decomposition may happen more rapidly. On the other hand, particles from mechanical damage are more likely to be larger, denser than seawater, and less uniform in size and can generally be expected to have the same properties as the intact coating. For these types of sinking particles, further degradation and decomposition may take longer, causing the material to persist for a long period. We recommend determining coatings' degradation and decomposition rates, as well as the bioavailability (i.e., the proportion of the total quantity of particles present in the environment that is available for uptake/ingestion by various marine organisms; see Botterell et al., 2019) of microplastics released from ships' coatings.

## Conclusions

While the scenarios for the release of microplastics from ships' coatings can be categorized (Figure 1), the types, amounts, fates, and environmental effects of the coating polymers—under each pathway and over time—are highly variable and poorly understood. Focused, interdisciplinary research efforts are needed to collect, aggregate, and interpret data to better understand the relative risks of release. In turn, this information will be used to develop or improve environmentally protective best-practices and regulations. Because different sectors (coating manufacturers, ship owners/operators, IWC service providers, and in-water maintenance and repair service providers) of the maritime value chain represent possible pathways for the release of microplastics, it is necessary that each sector investigate their respective areas, and they coordinate efforts between sectors and with academic and agency researchers. In doing so, a holistic view of ships' microplastics will emerge, allowing for successful environmental stewardship.

## Author contributions

MT led the overall project design, execution, and drafting of this manuscript. LD, CS, ZS, CØ, NO, and SD contributed information, expertise, and insight, and they assisted in drafting various sections of the publication. All authors contributed to the article and approved the submitted version.

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