HULL SCRAPINGS AND MARINE COATINGS

AS A SOURCE OF MICROPLASTICS

INTERNATIONAL MARITIME ORGANIZATION

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Published in 2019 by the
International Maritime Organization
4 Albert Embankment
London SE1 7SR
United Kingdom

Printed and bound by CPI Group (UK) Ltd, Croydon, CR0 4YY

Acknowledgements

This study was made possible through the funding from the UN Environment-led Global Partnership for Marine Litter (GPML).

IMO would like to thank the consultant, Dr. Simon Bray (AQASS Ltd) for his work in compiling the report.

Executive summary

Through a recent report, the International Union for the Conservation of Nature (IUCN) identified hull scrapings, marine coatings and anti-fouling systems as potential sources of microplastics to the oceans. The impacts of marine plastics and microplastics upon species and communities are increasingly recognised with concomitant regulation and public attention. Accordingly, through its mandate on the protection of the marine environment from shipping operations, the International Maritime Organization (IMO) conducted a literature review to assess current knowledge and data regarding marine coatings as microplastics sources.

The global annual production of plastics has increased, and the plastics waste stream exceeds production; up to 95% of marine waste is comprised of plastics. Whereas plastics were previously regarded as an eyesore, but of little significance as a pollutant, it is now recognised that uptake of plastics can impact species and communities directly and that they may bioaccumulate or be directly taken up by humans.

Whilst plastics suffer limited microbial degradation, over time they are known to break down to monomers with potential toxic effects. They can also be taken up by planktivorous and particulate filter feeding species where they may affect biophysical processes (e.g. respiration, growth, etc.). Microplastics (generally agreed to be of a size less than 5 mm) have also been shown to sorb contaminants such as heavy metals and organic pollutants, with some organism guts having higher contaminant levels than the surrounding sediment.

Microplastic sources include the breakdown of larger terrestrially-based material through light, wave action, general abrasion, and through waste water discharge with material such as micro-fibres from clothing. Shipping is identified as a source of plastics, though limited data are readily apparent and there is little mention of marine coatings as a source of microplastics.

It is known that anti-fouling systems and marine coatings in general commonly contain a relatively high content of a polymer material (e.g. epoxy or acrylic). Nonetheless, while the release of biocides and heavy metals from marine anti-fouling systems and, to a lesser extent, other coatings has been considered, the issue of plastics has seen limited attention. Some research has identified microplastics from marine paints in sediment, and other work identified that shipyard maintenance may transport microplastics by air or runoff but in-water hull cleaning was not considered. Further, work shows that general operation emits copper and biocides from vinyl and epoxy coatings, which increases significantly during cleaning maintenance. However, the research reviewed did not consider microplastics release.

Limited work does begin to recognize marine coatings as a source of possible microplastics, particularly self-polishing anti-fouling products, which are designed to slough off during a ship's normal operations. However, specific studies on this matter could not be identified.

In-water hull cleaning is known to cause loss of some viable biological material, though collection rates are claimed to be high; it also increases release rates of toxic biocides and metal compounds to surrounding waters. Whether abrasive hull cleaning also causes loss of microplastics is not known, but it is possible, because hull coatings are often designed to slough off, and further research is needed. Additionally, the hull cleaning industry is growing in some geographic areas; therefore studies are needed to determine whether sensitive ecosystems and food webs may be affected by resultant micro-plastic material.

Finally, this study identified important data gaps and made suggestions for subsequent research into whether ship coatings are an important source of microplastics to the ocean. If so, the overall relative contribution to ocean microplastics from ship coatings, as well as the individual contributions from the normal use, maintenance and cleaning of coatings, need to be determined as the first step in further research efforts with a view towards informed management.

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1. Introduction

1.1 Rationale

A recent study by the International Union for Conservation of Nature (IUCN) identified marine coatings and hull scrapings as possible sources of microplastics, with potential impacts on marine systems. This microplastics release may be through the normal function of anti-fouling systems (AFS) and other marine coatings during ship operation or in-water or dry-dock maintenance, such as hull cleaning and coating replacement. However, at present there is insufficient knowledge about the qualitative and quantitative contributions of microplastics from these sources. Accordingly, an overview / review was requested of where data gaps may exist, thus highlighting where research could be beneficial in informing possible future actions. This was to be undertaken from the perspective of International Maritime Organization's (IMO) mandate, including the Anti-Fouling Systems Convention (AFS Convention), the Biofouling Guidelines, which inter alia aim to address the best practices for the management of hull fouling and for the safe removal and disposal of anti-fouling wastes, and the London Convention and Protocol, one of the first global agreements towards protection of the marine environment (also see Section 3.1).

Against the broader background of IMO's work on the prevention of marine pollution, the IMO Assembly, at its 30th session (27 November to 6 December 2017), acknowledged the ongoing problem and growing recognition of marine plastic pollution. This requires further consideration as part of a global solution within the framework of ocean governance, in pursuance of SDG 14's target to prevent and significantly reduce marine pollution of all kinds by 2025 (SDG 14.1). The Assembly referred this matter to the 72nd session of the Marine Environment Protection Committee (MEPC 72) for detailed consideration and action as deemed necessary.

Pursuant to the above, MEPC 72 (9 to 13 April 2018) agreed to include a new output "*Development of an action plan to address marine plastic litter from ships*" in the 2018-2019 biennial agenda of the MEPC, with a target completion year of 2020 (IMO, 2018a). The new output was included in the agenda of MEPC 73 (22 to 26 October 2018), which considered several relevant proposals and adopted the *Action plan to address marine plastic litter from ships* (IMO, 2018d), with the aim of enhancing existing provisions in IMO instruments and potentially introducing new supporting measures to prevent plastic pollution from ships.

IMO takes an active stance against marine pollution (e.g. see IMO, 2018b) including from anti-fouling compounds through the AFS Convention, the Biofouling Guidelines and the London Convention and Protocol. For example, the interest of IMO in microplastics in general is complemented by further research into their sources and fates, as demonstrated by this study.

With specific regard to anti-fouling systems, the AFS Convention regulates the use of harmful anti-fouling systems on ships. The AFS Convention initially included controls on tributyltin anti-fouling paints, but the Convention also incorporates a mechanism for adding controls on further substances and, at present, there is an ongoing consideration of cybutryne. It is noted that, in addition to the AFS Convention, some individual nations have additional restrictions. For example, these include the United Kingdom ban on the biocides Irgarol 1051 and Diuron, Sweden's strict biocidal paint regulations for use on recreational vessels (Swedish Environmental Protection Agency, 2015) and the intended (initially scheduled for 1 January 2018 though currently delayed) ban on copper-based antifouling paint use on recreational boats in Washington State, United States (Washington State Legislature, 2011).

Regarding biofouling, the IMO's Biofouling Guidelines may be updated and/or enhanced as part of an upcoming review, including an evaluation of their effectiveness, which is expected to be carried out by the IMO Member States in 2020-2021. Furthermore, to support implementation of the Biofouling Guidelines, IMO initiated the GloFouling Partnerships project in 2017, which aims to build capacity in developing countries to prevent species invasions from biofouling. In addition, GloFouling activities are expected to contribute to the ongoing review of the Biofouling Guidelines.

Marine plastics debris and microplastics, and their potential effects on marine ecosystems and possible bioaccumulation to higher organisms, are areas of increasing research and regulatory focus (Fossi et al., 2014; Law, 2017). This perhaps reflects changing attitudes and awareness, as science has shown for considerable time that marine plastics (e.g. Derraik (2002) for review) and microplastic waste (e.g. Shaw and Day (1994)), have deleterious effects on marine species and communities and can bioaccumulate or pass directly to humans. Public awareness and, by extension, legislation and commercial environmental management and opportunities (e.g. Recycling Technologies Ltd) are increasing. For example, in March 2018 the United Kingdom Government launched a consultation on single plastics use and attempts to reduce associated waste indicating increasing national attention to the issue.

It is important to note that general interest in marine plastics and microplastics is reflected in other regional approaches, that are perhaps complementary to UNEP and IMO approaches to future management of the issue. For example, the European Union Marine Strategy Framework Directive (MSFD 2008/56/EC) aims to achieve effective protection of the marine environment across Europe. In this regard, microplastics have been included in the MSFD as Descriptor 10 in the Marine Litter section (adopted by the European Commission, January 2018). Other nations are addressing the microplastic and cosmetic microbeads issue with bans on microbeads in cleaning products and, regarding microplastics in general, Australia calls for a "cooperative approach from all levels of Government in Australia as well as industry" (Parliament of Australia, 2016).

1.2 Study objectives

This review is intended to assess the current international state of knowledge on microplastic release from hull scrapings and marine coatings (including AFS, foul release, hard coatings and general copolymer paints for use in a marine / ship application) and to identify key data gaps.

The expected result of this study is a review to inform assessment of the qualitative and quantitative aspects of the contribution of hull scrapings and marine coatings as a source of microplastics.

This will be achieved through:

1) Review of available literature and any research data considering relevant anti-fouling system types, etc.; and
2) Identification of knowledge gaps leading to suggestions of where further detail and/or data may be required to assist IMO in understanding the issue leading to future management as and if required.

2. Plastics in marine environments

2.1 Background

A 2016 IMO study was produced after Member States requested more robust approaches to dealing with marine waste, particularly plastics (IMO, 2016). In the report, a paper by Santos and Duarte (2015) showed that the global annual production of plastics was around 280 million tonnes, with the majority comprised of single-use disposable items. The Santos and Duarte (2015) data was from 2011; the latest values available for 2015 (though not available at the time of the IMO report) are 322 million tonnes (Plastics Europe), showing a growth between 2011 and 2015 of approximately 13%.

In relation to plastic waste, Moore (2008) showed that from the 1980s to 2000s plastic waste had outstripped production, clearly illustrating the development of plastics as a waste material. Moore (2008) further showed that from 1970-2003 plastics became the fastest growing household waste stream and, most significantly, it was reported that marine waste was then 60-80% plastic with levels as high as 90-95% in some areas, and that primary recovery (recycling) levels for plastics were as low as 5%. The problem of plastic pollution has recently been highlighted by media and thus public awareness may be driving an attitude of change towards this source of pollution. This also appears to be somewhat changing attitudes of plastics producers, of which Moore (2008) quoted Derraik (2002) to show that at that time the attitude of the plastics industry was that the materials were a minimal contributor to overall waste and the only real issue from this was a visual rather than a toxic pollution problem.

Contrary to the previously existing opinion that marine plastic pollution was no more than an eyesore, research has shown that plastics have significant impacts and implications for marine and avian species (Wilcox et al., 2016). These effects also encompass wider ecosystems and communities through mechanisms including microplastic bioaccumulation (Wang et al., 2016) and direct pathways (e.g. sea-salt) to humans (Yang et al., 2015). However, comments on impacts to humans given here should be balanced with information from Rist et al. (2018) which acknowledges that there is a human / bioaccumulation route for plastics, but suggests that the risk is relatively minor. Rist et al. (2018) commented that the focus on humans and microplastics has the risk of taking attention away from the causal situation, i.e. how humans consume and dispose of plastics and their ongoing environmental impact.

2.1.1 Plastics and associated pollution

Other than visual impact, un-degraded plastic material may not be regarded as a toxic pollutant as these compounds comprise long chain crossed molecules with poor bioavailability and limited susceptibility to microbial degradation (Krueger, Harms and Schlosser, 2015). However, plastic particles have been shown to be taken up into the food web by zooplankton (e.g. Desforges, Galbraith and Ross, 2015) where biophysical effects may occur, such as influence on organism respiration and reproduction rates and their growth and survival (Wright, Thompson and Galloway, 2013; Paul Pont et al., 2016).

In addition to biophysical effects, through bioaccumulation and direct uptake plastics may impact higher organisms through the food web, or directly via planktonic filter feeding, for example basking sharks and some whale species (Fossi et al., 2014; 2016). Importantly, as plastics can accumulate in the gut of feeding organisms (zooplankton, avian species, cetaceans (Wilcox et al., 2016)), it is also known that plastic species have the ability to sorb organic pollutants (e.g. PAHs[1], PCBs[2] and DDT[3]) and heavy metals (Rochman, 2015). Through this, bioaccumulation and biomagnification of contaminants can lead to them reaching levels reported as up to ten times higher in organism guts than those in surrounding sediments (Van Cauwenberghe et al., (2015), from IMO, (2018c)). Brennecke et al. (2016) showed that organic polymer microplastics have strong attraction to heavy metals and that this was likely related to "cations or complexes onto charged sites or neutral regions of the plastic surface". Brennecke et al. (2016) went on to show that differing plastics sorption rates would respond differently to contaminants (via hydrophobicity, diffusivity, etc.) and importantly the work quoted a paper by Holmes (2013) which identified that pollutants bound to plastics are highly bioavailable. The interest in the fate of plastics within the marine environment is highlighted by the development of organisations such as International Pellet Watch who are involved in ongoing global studies of plastics sorption of contaminants in marine environments; their data clearly shows concentration patterns for marine plastics near heavily industrialised areas.

Brennecke et al. (2016) commented that microplastics can play an important vector role in heavy metal transport and considered copper (Cu) and zinc (Zn) transport from AFS. Interestingly, Auta, Emenike and Fauziah (2017) also reviewed microplastics as a pollution pathway and commented that metals from anti-fouling compounds bonded to plastics, though neither study considered plastics from anti-fouling systems or other marine coatings themselves. Work has shown that plastics can be taken up by filter feeding species potentially creating a direct pathway to humans (e.g. Phuong et al., 2017). Van Cauwenberghe and Janssen (2014) showed that mussels and oysters in Europe contained microplastic particles and estimated that Europeans with a diet high in shellfish may have annual exposure to 11,000 microplastic particles, though the toxicity of this to human health cannot yet be reliably assessed (though see Rist et al., 2018). Accordingly, it may prove valuable to consider microplastics from AFS and their ability to bond to heavy metals or biocides associated with anti-fouling systems and marine coatings, and thus their potential intrusion into ecological and human food pathways.

Though new un-degraded plastics may be considered relatively inert, work suggests that more than 50% of plastics produced are hazardous "based upon their constituent monomers, additives and by-products" (Rochman, 2015). Further, whilst these may be relatively chemically inert, breakdown can lead to monomer releases which are known to be toxic (Rochman, 2015; from IMO, 2018). For example, bisphenol may be a disruptor of endocrine function and styrene has also been implicated in this area, although a direct endocrine effect for styrene in marine and aquatic systems needs to be clarified (e.g. Gelbke et al., 2015). Styrene is also associated with carcinogenic and / or mutagenic responses and is listed as a toxic substance by the US EPA (United States Environmental Protection Agency), ATSDR (Agency for Toxic Substances and Disease Registry) and the OSPAR Commission (Rochman, 2015).

Of secondary interest, GESAMP (2015) shows calculations for the specific gravity of some plastic species. Whilst many plastics sink to the benthic habitat, accumulation of a biofilm or hydrophobic organic molecules (Kedzierski et al., 2018) on these fragments will mean they may be re-suspended, potentially being taken up by filter feeding and opportunist pelagic or scavenging intertidal species such as ghost crabs (Ocypode and Hoplocypode) (Schlacher et al., 2016) (Figure 2.1).

1 Polycyclic aromatic hydrocarbons
2 Polychlorinated biphenyls
3 Dichlorodiphenyltrichloroethane

Figure 2.1: Plastics near ghost crab burrows, Cape Vidal World Heritage Site, South Africa
Source: AQASS Ltd, (2016).

2.2 Microplastics

2.2.1 Definition

Law (2017) broadly defines microplastics as particles less than 5 mm in size, but notes that they "have also been defined as particles smaller than 1 mm (e.g. Browne et al., 2011) and have been functionally defined (at the lower limit) as particles retained by plankton nets or sieves with variable mesh sizes".

Importantly for ecological aspects, Law (2017) discusses that the smallest plastic particles detected are a few microns in size, but that nanometre-sized particles may also exist; however, no reliable detection method as yet exists to detect and identify plastic types. In terms of impacts on species, the size of microplastic particles is important; Almedia (2017) found that microplastics used for toxic effect experiments on fish were too large and for actual effect needed to be reduced to microgram size.

Overall, a number of papers and reports define microplastics as those with a size of less than 5 mm. However, if further clarification is sought, see Verschoor (2015), who seeks to provide a more precise definition of microplastics that may be applied during the development of legal / regulatory reduction goals. For this report, the definition of microplastics being less than 5 mm has been adopted; however, it should be noted that when discussed in the biological / bioaccumulation sense, the term "microplastics" includes particles in the order of micrometres (e.g. Phuong, et al., 2017) and nanometres (Law, 2017).

2.2.2 Sources of marine microplastics other than hull scrapings and marine coatings

Microplastics have a variety of sources, though research papers tend to highlight terrestrial (freshwater runoff and point source outfall) as major inputs. In this context, in April 2018 the United

Kingdom Government (Department of the Environment, Food and Rural Affairs) put out a research call to seek input to management of microplastics in freshwater and drinking water.

In a review, Auta, Emenike and Fauziah (2017) discussed primary and secondary microplastic sources and fates of these materials. Primary sources are generally recognised as those intentionally created as microplastics either for later plastic production (colloquially known as nurdles) or from hygiene washing products, etc. This category also includes, as is increasingly recognised, microfibres from washed clothing. Secondary microplastics are derived from the breakdown of macro-material (i.e. larger plastic items) due to physical abrasion or exposure to ultra-violet light (which leads to brittleness, thus enhancing wave and turbulence effects (Auta, Emenike and Fauziah (2017)). Secondary microplastics are also generated via slower oxidative, biodegradation and hydrolysis breakdown of larger plastic items (Lassen et al., 2015).

Law (2017) conducted research into sources of plastics into the oceans and their potential biological impacts. In this work it was reported that the major source of plastic waste to the oceans is poorly managed material on land (Figure 2.2). The only attempt to quantify this input on a global scale was by Jambeck et al. (2015), who estimated an annual input of 4.8–12.7 million metric tons in 2010, allowing for significant error. Law (2017) also concluded that shipping is an important source of plastics into oceans. Whilst many papers (e.g. Wang et al., 2016; Law, 2017; Lohr, et al., 2017) mention shipping as a source, little detail is supplied save for general statements and that dumping of garbage at sea is controlled under MARPOL Annex V. Further, under MARPOL Annex V, the discharge of plastics (as well as certain other garbage categories) is prohibited. As a result, a reduction in plastic debris from ships should be expected (Wang et al., 2016). Lohr et al. (2017) do mention microplastics being used on hulls as an abrasive cleaning agent and that shipping is a general source of abrasives through washing off of these compounds and of other general plastic waste material. However, there is limited mention of AFS or ships' hulls or superstructure as a source of microplastics.

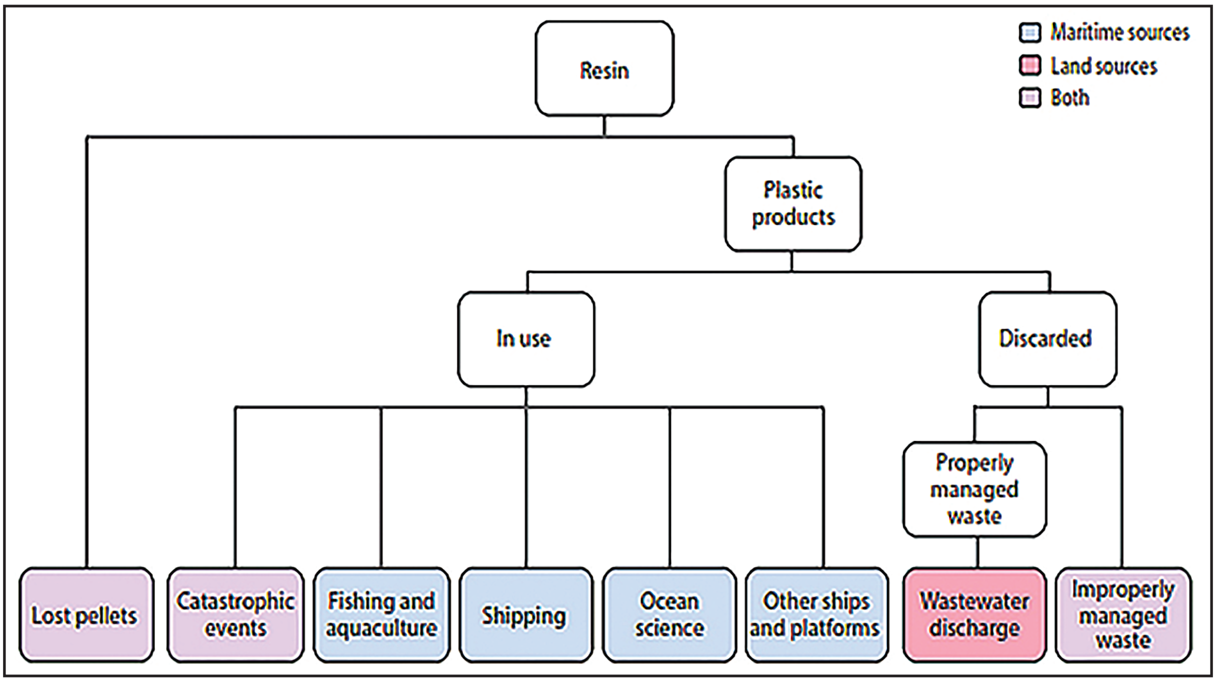

Figure 2.2: Flow chart of direct and indirect routes of plastics and microplastics to the ocean
Source: Law, (2017).

3. AFS, marine coatings and maintenance

3.1 Background

Since early ocean travel, biofouling and hull attack by boring species has been inhibited by various toxic (e.g. anti-fouling coatings / compounds) and physical (e.g. copper sheathing) barriers (for review see Yebra, Kiil and Dam-Johansen (2004)). Two IMO instruments are concerned with the issue of hull fouling and its prevention, the Anti-Fouling Systems Convention (AFS Convention) and the 2011 Biofouling Guidelines. Anti-fouling systems have followed several incarnations including the widely known and highly eco-toxic TBT, which was globally banned for use on ships by the AFS Convention. The AFS Convention aims to reduce or eliminate adverse effects on the marine environment from anti-fouling systems, and entered into force in September 2008. Further to this, the risk of potential transfer of invasive aquatic species via fouling growth on ship hulls and niche areas is addressed through the Biofouling Guidelines, which were adopted in July 2011. Finally, and preceding the AFS Convention and the Biofouling Guidelines, the London Convention (1972) and London Protocol (1996) were formulated to control and prevent dumping of wastes at sea; for an overview of relevant IMO activities, see Marine Environment pages at the IMO website under Our Work.

Many (though not all) modern anti-fouling paints follow a co-polymer approach where a toxic metallic / biocide compound is embedded within a polymer (plastic) resin by which, through interaction with water, a constant release rate of settlement-inhibiting organo-metals and biocide is achieved. Whilst not the aim of this report to list all anti-fouling types (see Omae, 2003 for chemical structure of several AFS compounds), other methods of toxicity delivery are available and include copper paints (also in a resin / polymer matrix), non-toxic (though see Pretti et al., 2013) foul release (silicone) coatings and non-toxic hard coatings (e.g. Davidson et al. (2016)). Importantly for this context, and to provide clarification, these latter paints include co-polymer compounds. These may be alkyls, epoxies, polyesters, vinylesters (e.g. acrylates see Zhou et al., 2015), etc., which are, in general, defined as plastics (Dyckman, 1974).

3.2 Ship coatings and microplastics

3.2.1 Background

A literature review was undertaken for this study to identify groups or individuals involved in research into the release of microplastics from anti-fouling systems, as well as other marine protective coatings. Limited information was found, though the issue of microplastics from AFS, hulls and general ship superstructure has received some attention. For example, in a review report on primary microplastics, Boucher and Friot (2017) identified that marine coatings are a source. They further discuss that marine paints comprise several plastic types mainly comprising epoxy, polyurethane and vinyl and lacquer within the coating matrix. Data for these observations are taken from OECD (2009) which also notes that releases of anti-fouling and coating compounds are related to maintenance activities such as pre-treatment (rubbing down, etc.), application and equipment cleaning. However, note that this comment does not include the possible release of microplastics from AFS due to in-water cleaning. This is also noteworthy in an OECD (2005) report which discusses anti-fouling compounds and, whilst not targeted at plastics release, but rather biocides, the report makes no discussion on in-water cleaning scenarios.

3.2.2 Microplastics, general operational release

It is evident that microplastics are justifiably receiving more attention with regard to their release from shipping-related activities and applications. There are several reports from Nordic nations on the issue (see below) where, in particular, recreational vessel use is very high. Chae et al. (2015) considered microplastics in coastal sea surface microlayers off the coast of the Republic of Korea. In this work it was shown that plastic particles of alkyd and styrene types associated with marine coatings were highly abundant in the surface microlayer. In addition, in previous works in the Republic of Korea, Song et al. (2014a,b) also identified alkyd and/or poly acrylate micro fragments from fibre reinforced plastic and from coatings. These can be associated with small boat hull or superstructure maintenance (abrasive cleaning, etc.) or potentially their break up at end of life (see IMO, 2018c).

Particle size of material recorded by Chae et al. (2015) was generally in the size range of 50-300 µm. This was considered equivalent to the general size range of living microplankton thus having significant potential to be taken up by planktivorous species with potential physical impacts on consuming species and through bioaccumulation and possible effects from associated pollutants (Rochman, 2015). They commented that the material was associated with shipping from the major hub port and ship repair area of Incheon, which is the industrial area of Seoul.

In the cases shown above (e.g. Chae et al., 2015; Song et al., 2014a,b), a major commercial shipyard at Incheon was suggested as a predominant source. Chae et al. (2015) reported that they tried to compare their results with other global findings, but found that this was not possible due to differing sample collection and analysis techniques. This may suggest the existence of unpublished data bases containing information of relevance to this topic. With the data disparity in mind, future management and recording may benefit from global standards on microplastic assessment and analysis.

A report by Sundt, Schulze and Syversen (2014) reviews microplastic sources and notes that much of the general research focus regarding ship maintenance and abrasive paint cleaning has been on heavy metals. The report summarises material losses including the work undertaken by OECD (2009) which is useful in terms of gaining some understanding of the quantities of microplastics that may be released from these activities. Based on an estimate that above 50% of marine paint is solids (higher solid content results in less dangerous solvents) of which about 50% is the plastics constituent, Sundt, Schulze and Syversen (2014) calculated that around 0.5 kg of dust material (plastics and related biocides / metals, etc.) is created per m^2 of ship hull during cleaning. They also mention paint lost in application (estimated by them at 30%) and that this tends to be mist material which coalesces to form particles in the microplastic size range (from Nordisk Ministerråd (1995)).

Sundt, Schulze and Syversen (2014) noted that OECD (2009) reported that around 6% of solid anti-fouling coating is lost directly to the sea during its lifetime with a further 1.8% lost during painting, 3.2% during cleaning maintenance and 1% from weathering. However, Sundt, Schulze and Syversen (2014) considered this an underestimate and suggested that, as smaller fragments are likely to be washed away, microplastic losses from a maintenance worst case scenario were at least twice that of the OECD assumption. This equated to an estimated tonnage of microplastic losses from Norwegian shipyards, etc., to be 330 tonnes per year with a fraction to soil and the remainder to sea. The report noted that the recreational sector also creates microplastic waste from both yards and owners working on their boats. Sundt, Schulzeand Syversen (2014) suggested that, in addition to microplastics from paint cleaning, there would also be associated dust from glass reinforced plastic hulls, though they considered this minimal. However, it was commented that for most recreational boat yards and public maintenance areas there is no control for plastic release. Therefore loss of paints (and fibre reinforced plastics) to air (and the sea / soil) was assessed to be significant, thus further suggesting that future control of these activities may be required and that, in Norway at least, attention was growing towards having formal dust management / collection systems in place.

Whilst work on loss of plastic compounds from marine coatings is very limited, and largely restricted to comments that the field needs attention, research by Schiff, Diehl and Valkirs, (2004) shows that copper emissions for hard vinyl and epoxy-based coatings on recreational boats as a result of normal operations were 3.7 and 4.3 μg/cm^2/day respectively. In addition, the copper emissions for vinyl and epoxy coatings from hull cleaning were 3.8 and 8.6 μg dissolved copper cm^2/cleaning event respectively. This suggests two things: 1) that hard vinyl coatings may give off less microplastic material during both normal use and cleaning operations than epoxy-based coatings, and 2) that (as intended) there is a general release of material which suggests that further work on plastics release is needed. Later research suggested that a loss ratio of 50% during the service life of copper coats on recreational vessels amounted to 15% of all external sources of copper released into German surface waters (Daehne et al., 2017), thus indicating that the loss of plastics may be similarly significant and need appropriate consideration.

As discussed above, Nordic nations have been investigating microplastic pollution from ship AFS and maintenance. The Swedish Environmental Protection Agency undertook a data review for sources of microplastics (Magnusson et al., 2016). This work confirmed the findings of Sundt, Schulze and Syversen (2014), i.e. that shipyards and marinas are sources of microplastics as a result of ship maintenance (cleaning, repair, etc.). Interestingly, and perhaps importantly, the report highlighted a difference in opinion of boatyard maintenance as a source of microplastic to soil then sea, with the Swedish report suggesting that this deposition route would result in high levels reaching the sea, the opposite of Sundt, Schulze and Syversen (2014). In relation to this, Magnusson et al. (2016) also reported that there are limited data on pathways from soil to sea. Thus the uncertainty and disparity on options of soil pathways of microplastics from shipyard / marina maintenance indicates that research or precautionary approaches may be required. In any event, research can progress and improve limited data on whether microplastics (and associated biocides and heavy metals) from anti-fouling / ship maintenance is an issue of sufficient concern.

In a 2018 report for DG Environment of the European Commission (Eunomia, 2018) it was stated that “the emissions of paint particles from ships, buildings and roads are largely theoretical. Whilst these surfaces are known to wear during their lifetime, the exact nature of the resulting particles is yet to be established.” However, as demonstrated above, work in the Republic of Korea by Song et al. (2014a,b) and Chae et al. (2015) shows that research has considered the nature of shipping paint particles and strongly identifies plastics associated with a variety of marine anti-fouling and corrosive protection coatings. Interestingly, the Eunomia (2018) report was somewhat critical of the paint industry. It was noted that “The paint industry itself, whilst cooperating with this project’s aims, does not appear to have studied the subject until recently and only in response to increasing concern”. Further to this, in noting that emissions factor estimates had been reduced, Eunomia (2018) stated that “there has been no empirical data gathered to support the assertions of the paint industry, therefore this source of microplastics should not be dismissed at this stage—especially these are direct emissions to the oceans”. Eunomia (2018) did go on to recommend field experiments to establish loss of paint particles during wear and use which, if put in place, ideally should be of a standardised nature through global cooperation, to ensure compatibility and repeatability of data collection. The fact that this report was produced in 2018, and clearly identifies a lack of supporting data for some factors and recommends collection of other data, recognises the general need for growth and possible management in this field. This highlights commonality in that almost all reports recommend more work, highlight limited data and suggest that, as shipping represents a direct input to oceans, data to support management is an imperative.

Finally, Lassen et al. (2015) consider metal and biocide losses from ships assessing release from above-water anti-corrosive paints and AFS and hull coating releases. Figures are calculated for Denmark, but are generally applicable for release calculations from commercial shipyards and recreational vessel marinas. Suggesting that use of coatings is moving toward two-pack epoxy paints, Lassen et al. (2015) quote OECD (2009) figures (see above) for releases during application and calculate percentage ranges for coating loss from shipyard maintenance as 2-20% (note the disparity with the assessment by Sundt, Schulze and Syversen, 2014 above) and suggest that recreational boat paint losses in Denmark will be higher.

Of considerable significance to this project, Lassen et al. (2015) discuss losses of microplastics from self-polishing (anti-fouling) paints and, as far as research for this project can readily identify, this is the only report that makes clear reference to the matter, though as shown above there is example work discussing in-water cleaning and normal use loss of anti-fouling metal compounds (Schiff, Diehl and Valkirs, 2004; Daehne et al., 2017). The authors stated that they could not identify studies on the subject. As no other research could be readily identified, it is apparent that the matter requires consideration being highly relevant to possible management of microplastic release from shipping. This is particularly so as the self-polishing method is specifically reliant on the sloughing off (through hydrolysis and erosion) of paint material to maintain efficacy of anti-fouling compounds. Furthermore, as self-polishing paints are intended to slough off and are commonly a mix of metals, biocide and plastics, the risk of plastic particles binding to metals being released from coatings also needs consideration, as does the size range of plastic particles released in relation to paint type, plastics compound, etc.

3.2.3 Microplastics from in-water hull cleaning

It is important to note that none of the reports or papers referred to above discusses the hull cleaning industry and possible losses of microplastics from underwater remote (ROV) cleaner or diver activities. A brief reference to cleaning and normal mode of action concerns regarding AFS polymer loss was made by Cattrijsse et al. (2013) in relation to attention drawn by scientists.

Whilst literature on in-water cleaning exists (there are numerous studies on biocide and invasive species release), none discussing microplastics in detail with specific study of polymer particles release were readily identified for this project. Research and review work has shown that in-water cleaning can lead to biocide / paint particle loss and release of viable invasive / exotic species transferred through the removal of biofouling. For example, Zabin, Davidson and Ruiz (2016) looked at the issue of biocide loss and species transfer, but, whilst this is a major report, it does not consider microplastics release suggesting this was not in the remit or not considered an issue at the time.

In the hull cleaning industry, while many contractors who carry out diver or ROV in-water cleaning advertise that their technology captures the majority (if not all) of waste material (e.g. companies in Singapore, the United Kingdom and West Africa), research suggests that, as yet, capture is not 100% effective and it appears that no work has been undertaken on microplastics release and capture rates / success during in-water cleaning.

Zabin, Davidson and Ruiz (2016) discuss in-water cleaning options for ship hulls and mention that currently there are no universal standards for the performance (waste capture, cleaning effectiveness, etc.) of these cleaning systems and activities. Published reliable data regarding the efficacy of waste capture systems are limited, although Morrisey et al. (2013) quoted Hopkins, (2010) who showed that, on average, 3.8% (±0.8% SE) of biological material removed during cleaning was lost to the environment, but these losses could be up to 9%, and earlier work by Hopkins and Forrest (2008) showed that most in-water cleaning systems did not have waste capture systems and that biological material losses could be up to 12% (5.6% mean ± 2.3% SE). The relatively high variance to mean value suggests that further sampling may be needed to ensure data are representative of biological material loss (Figure 3.1). In addition, considering that biotic waste is larger in size than microplastics, this suggests that capture systems may be considerably less effective against loss of contaminants including microplastics, though more research on this assumption is required, perhaps in discussion with cleaning system designers and operatives.

Aggressive cleaning has also been shown to reduce the efficacy of AFS coatings through excessive loss of metals / biocides and through roughening of the coating, potentially providing a surface at the microscopic scale to which organisms can attach (Oliveira and Granhag, 2016). In addition Oliveira and Granhag (2016) show that attachment of macro-foulers to epoxy based coatings is very strong and they recommend not cleaning such macro-fouling underwater due to coating damage and loss of biological material through shell shattering. This aspect acknowledges that there is coating damage and indicates that, as this is realised, there is a concomitant loss of polymer material potentially becoming biologically available microplastics.

Figure 3.1: Underwater hull cleaning with no capture system evident
Source: AUSMEPA (2010).

Many hull cleaning companies claim significant recovery rates for biological material (contaminants such as heavy metals and polymers are not generally mentioned) for both remotely operated cleaning equipment and for diver operated brushes etc. These claims tend to be made on promotional material and web sites developed to sell in-water cleaning services. While the majority of in-water hull cleaning company sites viewed made no claim for recovery of material, biological or otherwise, some company web sites visited had claims regarding biological material recovery which were generally high (upwards of 95%). For those that did claim high recovery rates, no supporting data or research were readily available. Interestingly, one company site discussed a policy not to undertake in-water cleaning where pollution from release of toxic material from hull coatings may be a risk.

Whilst some of the in-water cleaning industry states that waste capture rates are high, Sundt, Schulze and Syversen (2014) recommend that the only way to undertake in-water cleaning and to capture all waste material (presumably biological and paint / biocide) is in an isolated water body. However, whilst available research is based on biofouling material, the work by Woods, Floerl and Jones (2012) shows that even dry-dock filter / flush systems can still let material through though at considerably reduced extent to in-water cleaning. Thus, considering differing industrial and research opinions on the effectiveness of pollutant capture technologies and lack of firm guidelines on best practice, it appears that, in relation to microplastics (and associated micro pollutants) from marine coatings, further research on this issue is required.

Zabin, Davidson and Ruiz (2016) commented that, due to regulation and restriction on in-water cleaning in some areas, operations at sites where the activity is not restricted is seeing an increase. In a risk management study undertaken for Hawaii, it was noted that in-water cleaning releases possibly viable organisms and paint components. The authors noted that in-water cleaning was increasingly restricted or banned in other locations thus possibly placing Hawaii at increased unregulated risk from the industry as other areas control the practice. On the other hand, in some areas such as the United Kingdom, the practice is seeing growth, with relatively recent licensing in Portland Harbour and the Port of Southampton advertising the practice through contractors. It should be noted, however, that the Port of Portland conducted a risk assessment before the in-water cleaning was permitted. Their contractor also claims that all waste is collected, and that the process is approved for cleaning silicone foul release paints (which can be fragile when abraded) and is sensitive to hull coatings in general (though see concerns regarding cleaning damage to hulls above, Oliveira and Granhag, 2016). Thus it is assumed that damage is minimised, and debris collection is optimised. However, the process may not have been assessed for microplastics release; there is a shellfishery industry near Portland Harbour (Cefas, 2008), which may prove to be a useful source of future monitoring data at this location through bivalve filtration of plastics.

Pagoropoulos et al. (2017) undertook a Life Cycle Analysis (LCA) to consider the economic benefit and related environmental impact from in-water cleaning of merchant ships. In this study, the focus was on self-polishing anti-fouling compounds with related acrylic copolymer strategy. The work considered costs and benefits, and Pagoropoulos et al. (2017) noted that the regulation of in-water cleaning lacked uniformity. This is among the issues being addressed through the GloFouling project, which will include the development of measures at the national level to promote uniform implementation of the Biofouling Guidelines.

Noting that several ports are hubs for in-water cleaning (e.g. Singapore), Pagoropoulos et al. (2017) showed that, for example, in South Africa all in-water cleaning is banned apart from at offshore anchorages, thus highlighting a global disparity in in-water cleaning approaches and differing interpretation of risks and potential financial opportunities. The work goes on to discuss the assessed risks associated with in-water cleaning and, although AFS factors are specifically considered, the research does not include any detail. For this report, the lead author (Aris Pagoropoulos) was contacted and the question regarding microplastics release from anti-fouling systems was discussed. He was happy to consider this and stated that, during the study, he asked the paper's (Pagoropoulos et al. 2017) co-authors, who have significant LCA and industry experience, about the epoxy (i.e. plastics); this did not receive a satisfactory response (Pagoropoulos pers. comm., 2018). A further comment was made that LCA has limitations and that from information given to the authors the article was written "on the implicit understanding that the impact of epoxy emissions is basically zero across every impact category". Pagoropoulos (pers. comm., 2018), further commented that "you have a couple of tons of epoxy on each ship that over the five years' lifecycle just wash off like soap. Where does it go? And what is the impact of it?"

Hull cleaning activities are generally associated with large ports and, potentially in a more unregulated fashion, recreational marinas. There is concern and impact associated with pollution from AFS and research has shown that copper release increases significantly with underwater cleaning of anti-fouling systems (Schiff, Diehl and Valkirs, 2004; Earley et al., 2014). Differing amounts released were related to cleaning methods used, e.g. hard brush, soft wipe grooming, etc. (Davidson et al., 2016; Oliveira and Granhag, 2016), but nonetheless greater levels are recorded when cleaning, including from epoxy and vinyl coatings (Schiff, Diehl and Valkirs, 2004; also see Morrisey et al., 2013, p. 64). Whether this also translates into loss of microplastics underwater whilst hull coatings are being cleaned, and evidently leaching increased metals and possibly biocide, depending on coating type (Schiff, Diehl and Valkirs, 2004), requires greater consideration. On the latter point, the work by Morrisey et al. (2013) is a substantial and comprehensive report that specifically investigates in-water cleaning and contaminant release, but the document makes no mention of microplastics. However, even in light of work showing that in-water cleaning does lead to increased metals and biocide release, it should be noted that in-water cleaning has also been viewed as a potentially beneficial approach in management of risk. Provided waste material is captured and the work is done "properly, it may provide biosecurity benefits in certain situations" (Woods, Floerl and Jones, 2012).

Overall, in-water cleaning of AFS, foul release and other marine coatings is relatively well considered in literature from the point of view of release of biofouling, as well as the release of biocide and metals, particularly when cleaning is too aggressive (Oliveira and Granhag, 2016). However, it appears likely that this field may benefit from research into the release of microplastics from hull cleaning. This may be particularly pertinent as it has been shown that aggressive brush cleaning can damage anti-fouling systems.

The IMO's Biofouling Guidelines contain guidance on in-water cleaning, which may be updated and/or enhanced as part of the review of the Guidelines.

4. Next Steps

4.1 Data gaps

Efforts have been made here to identify research and review reports regarding the release of microplastics from anti-fouling paints, other hull paints and marine coatings through normal wear, or when cleaned, maintained or abraded. As is widely recognised, there is considerable research over many years of the toxicities of anti-fouling types and loss of this and biofouling from ship hulls, particularly when being cleaned in water. It is only very recently that attention has focused on microplastics in marine systems and, in the case of this study, on the implications of maintenance to AFS and other marine coatings through in-water cleaning and shipyard / marina services. However, apart from minimal comments in researched literature that the loss of plastics from AFS may be an issue (e.g. Lassen et al., 2015; Boucher and Friot, 2017; Eunomia, 2018), direct research on this possibility was not readily apparent. This review, as well as personal communications with an expert in this field, did not readily reveal any research directly investigating microplastics from anti-fouling systems and/or marine coatings, though this may be available, but as yet unpublished or accessible.

This relative lack of information has led to data gaps which may benefit from research to inform future policy and management of microplastics from AFS and ship coatings, including:

- Whether there is presence of microplastics in the ocean, through activities such as hull cleaning, replacement of hull coatings, and the normal wear of anti-fouling hull coatings;
- If identified as a source, clarify, where feasible, the relative contribution of microplastics to ocean systems against other sources such as terrestrial runoff, etc.;
- A clear identification of the behaviour of differing plastics from AFS / marine coatings demonstrating:
    - Wear rates of the differing polymers (e.g. see Schiff, Diehl and Valkirs, (2004)) in amount released per surface area (e.g. per m^2), from normal abrasion and cleaning (onshore and in-water) and differing cleaning / grooming methods (e.g. see Oliveira and Granhag, 2016);
    - Size of marine paint plastics released and the related ecological / food pathway risk from these;
    - Whether plastics released from AFS through natural wear or in-water cleaning can readily adsorb biocides and/or metals from AFS / hull coating paints and organic / inorganic pollutants in the water column;
    - The ability for differing AFS / marine paint plastic types to sorb already extant contaminants (organic / heavy metal, etc.) and related risk, through possible differing internal desorption, etc., to benthic / pelagic species through bioaccumulation;
    - Fate of microplastics, i.e. partitioning of the differing plastic types between the sea surface micro layer and possible deposition in sediment / benthic habitats and the related contaminant levels which may overcome plastic type buoyancy leading to deposition;
- The efficacy of in-water cleaning systems and their ability to collect microplastics (as and if significantly released from ROV or diver cleaning) at sizes important for intentional or unintentional uptake by marine species;

- In-water cleaning areas, dry-docks and outlets of dry-dock flushing systems as possible “hotspots” of microplastics associated with AFS and marine paints;
- The possible pathway of dispersion of plastics from all at potential risk source activities towards ecologically sensitive ecological communities and species and through food webs, potentially to human receptors;
- The pathway of soil to sea (from on-land cleaning of AFS / marine paints) of cleaned plastics and associated contaminants from shipyards / marinas;
- Options for control and management and related commercial implications.

4.2 Recommended research

Recognising that research is generally funding-limited, the findings given above regarding data gaps and knowledge limitations regarding microplastics release from AFS / marine paints are presented here as possible priority studies to inform the potential need for future management and/or policy development. This is based on impressions gained through this review and comments from primary researchers in the field.

It is important to understand if activities such as hull cleaning, replacement of hull coatings, and the normal wear of anti-fouling hull coatings contribute to the presence of microplastics in the ocean. This has implications for many of the other data gap areas. If, for example, microplastics are not released from marine coatings via normal use or abrading (in whatever form) in significant quantities, then further research on pathways, partitioning, pollutant uptake, risk to ecosystems / species and to humans through the food pathway may be negated. Recognising that microplastics are present in the food supply and marine species in general, if there is not proven to be a significant source from marine paint use / in-water cleaning, etc., research such as partitioning, pollutant uptake, etc., may be negated. However, should further work be deemed appropriate, it is recommended that:

- An initial study be undertaken on differing copolymer AFS / marine paint types to assess microplastics loss from normal use and in-water / onshore cleaning / cleaning types;
- Research be carried out to establish if the size of material lost is significant in relation to biological / ecological significance;
- An assessment be undertaken to consider commercial implications from possible management options to the shipping maintenance industries.

From the above recommendations it is intended that the necessity for subsequent more detailed studies may be established, though this is not presented as a definitive list and may be considered for additional areas of research. Accordingly, it is recognised that there may be other factors requiring further consideration not discussed here, which may influence necessary studies and preferences (e.g. potentially with input from ship maintenance industries and regulatory bodies with experience of managing these issues).

5. Summary and conclusions

This study and review considers readily available data, research and opinion on the possible release of microplastics from marine coatings (including biofouling management products), the fate of this material and potential impacts.

In a short background to this study, the issue of microplastics and their agreed definition (regarding size) has been noted. For this study, whilst microplastics have been regarded as being those below 5 mm overall size, the bulk of the literature considering biological implications suggests that particles in the order of microns may be relevant as these may be taken up by plankton / planktivorous species, thus leading to possible bioaccumulation. However, in terms of plastic particles potentially given off by marine coatings and related activities (normal use, maintenance, abrasive cleaning), it will be important to establish what may be seen as an "acceptable" size range and whether this then warrants further consideration in terms of environmental and ecological risk bearing in mind that, even if particles are above an agreed size limit, they will subsequently degrade to smaller sizes in time.

Marine plastics pollution has seen a significant upsurge in public interest in recent times. This may be attributed to attention from the media and increasing efforts to restrict plastic use and to find alternate materials, and is perhaps a demonstration of consumer power over commerce. However, this may not extend to the shipping sector. Although this report has attempted to highlight studies and data on the release of microplastics from marine paints and coatings, very little practical research or knowledge on the topic was found.

It appears likely that appropriate research or further detailed contact with researchers in the field may be needed to at least assess the likelihood of microplastics release from marine paints, in particular anti-fouling systems. If the release of microplastics is established, further research questions regarding pathways and possible toxicity will be necessary, which would then inform the need for management and regulatory interventions at the national and international levels.

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Appendix — websites not in reference list

Websites not in references. Accessed March-June 2018.

Name	Web Address in order appearing in text
IMO Anti Fouling Systems (AFS) Convention	http://www.imo.org/en/OurWork/Environment/Anti-foulingSystems/Pages/Default.aspx
IMO Biofouling Control and Guidelines	http://www.imo.org/en/OurWork/Environment/Biofouling/Pages/default.aspx
IMO London Convention and London Protocol	http://www.imo.org/en/OurWork/Environment/LCLP/Pages/default.aspx
SDG 14. Sustainable Development Goal 14	https://www.un.org/sustainabledevelopment/oceans/
UK Govt. Plastics Consultation	https://www.gov.uk/government/consultations/tackling-the-plastic-problem
EU, Marine Strategy Framework Directive	http://ec.europa.eu/environment/marine/eu-coast-and-marine-policy/marine-strategy-framework-directive/index_en.htm
EU, Descriptor 10, Marine Litter	http://ec.europa.eu/environment/marine/good-environmental-status/descriptor-10/index_en.htm
International Organization for Standardization – World Plastics Production	https://committee.iso.org/files/live/sites/tc61/files/The%20Plastic%20Industry%20Berlin%20Aug%202016%20-%20Copy.pdf
IMO Marine Environment	http://www.imo.org/en/OurWork/Environment/Pages/Default.aspx
IMO Our Work	http://www.imo.org/en/OurWork/Pages/Home.aspx
International (plastic) Pellet Watch	http://www.pelletwatch.org/
GloFouling Partnership	http://www.imo.org/en/mediacentre/pressbriefings/pages/20-biofouling.aspx