Emission of microplastics from maritime paints

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Emission of microplastics from maritime paints

Abstract

Research on microplastic pollution is currently a well-established field and has gone beyond the focus of academia to the general public. It was speculated in 2019 that the amount of microplastics in certain oceanic compartments would double by 2030. On the global point of view, key sources of primary microplastics released into the ocean, are (1) plastic pellets, (2) synthetic textiles, (3) tyres, (4) road markings, (5) marine paints, (6) personal care products and (7) city dust. Paints used for marine application can be damaged or degraded due to several factors, e.g. solar radiation, high salinity, temperature fluctuation, wet-dry cycles, mechanical friction, macro and micro living species. Such processes alter both physical and chemical properties of the paints and most often lead to generation of secondary microplastics. In 2017 marine paints were reported to contributed to 3.7% of global releases of microplastics to the world oceans. The most recent published technical report in 2022 indicated contribution of marine paints as high as 7%. Human exposure to microplastics may occur via ingestion, inhalation and dermal contact due to the presence of microplastics in products, food and air. Annual microplastics consumption, focusing on the American diet, ranges from 39 000 to 52 000 particles depending on age and sex. When inhalation is taken into account, these estimates increase to 74 000 and 121 000. The accumulation of microplastic particles in humans may lead to health risks, e.g. cytotoxicity, hypersensitivity, unwanted immune response, and acute response like hemolysis. As exemplified above, hazards of microplastic pollution needs a call for attention to reduce the plastic debris in marine environment. This report aims to investigate the current literature on the topic of microplastics, with special attention to microplastics from marine coatings in marine eco systems. The conclusion from this study is that research to find alternative coating systems for marine application and for material in contact with drinking water and food is needed. The authors suggestions are that such research should focus on:

- Efforts to produce paint that can be bio-degraded once it become microplastic litter
- Efforts to produce plastic free paints with adequate anticorrosion/ antifouling properties.
- Efforts to replace toxic, bio-accumulable materials/ ingredients from marine paint formulations
Background

Research on microplastic pollution is currently a well-established field and has gone beyond the focus of academia to the general public (Frias et al., 2021). The amount of microplastics in certain oceanic compartments was speculated in 2019 to double by 2030 (Hale et al., 2020).

During June-July 2014 and in June 2015, plastic samples were collected from surface water in Stockholm archipelago and Gotland, respectively (Gewert et al., 2017). The samples were visually sorted and characterized using Fourier transform infrared spectroscopy (FTIR). The samples from Stockholm archipelago demonstrated plastic concentration within the range of 0.19 to 7.73 plastics/m³ and were originated from four main categories, (1) plastic fragments, (2) microplastic, (3) paint flakes, and (4) fibers. In the case of open Baltic sea (Gotland), plastic concentration was observed within the range of 0.11 to 0.87 plastics/m³. In August 2014, another study was conducted in Skagerrak, Kattegat, Baltic Sea and Gulf of Bothnia (Schönlau et al., 2020). Open surface water sampling started in Gothenburg (west coast) and ended in Stockholm (east coast). Microplastic particles were found in all 12 samples from west to east coast. The works done in Sweden indicate that microplastic pollutions is ubiquitous in Swedish surface waters.

It is well known that microplastics may have adverse effects on marine ecosystems. In addition, bioaccumulation may lead to microplastic exposure to humans. The effects of microplastics on humans is not well understood but interests in the research area has increased significantly over the past few years. As examples mentioned above, hazards of microplastic pollution needs call for attention to reduce the plastic debris in marine environment.

Aim and scope of this report

The aim of this report is to summarize published information on emission of microplastics from marine paints. The content includes

- brief definition of microplastics
- effects on human and marine life
- brief concept of marine paints
- situation of marine paints as a source of microplastics pollution in Europe
- list of characterization techniques for microplastics
- proposed research activities for mitigation

The sources of information are scientific papers, technical reports and valid websites. Scientific papers were searched with combination of keywords, e.g., microplastics, paints, from Scopus and Google Scholar with limited years during 2012-2022. Technical reports and websites search were conducted using Google.
Microplastics

Microplastics are small debris of various plastics originating from different sources of man-made polymers. Microplastics are generally classified by size but there is currently no clear consensus on a standardized classification of microplastics. Three different classifications that has been used frequently are as follows:

- micro-debris with a diameter below 5 mm.
- plastics with size range of 1-5 mm,
- small microplastics (20 μm-1 mm) and large microplastics (1-5 mm).

There have been attempts to find a definition of microplastics, one definition proposed by Verschoor et. al., is given in Table 1 (Verschoor et al., 2016). Another definition has been proposed by Frias and Nash (Nash, 2019) “Microplastics are any synthetic solid particle or polymeric matrix, with regular or irregular shape and with size ranging from 1 μm to 5 mm, of either primary or secondary manufacturing origin, which are insoluble in water”

Table 1 Microplastic definition

<table>
<thead>
<tr>
<th>Property</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition</td>
<td>Synthetic polymer-based materials</td>
</tr>
<tr>
<td>Physical state</td>
<td>A substance that is not a liquid or gas</td>
</tr>
<tr>
<td>Size</td>
<td>&lt; 5 mm</td>
</tr>
<tr>
<td>Solubility</td>
<td>&lt; 1 mg/L</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Degradability</th>
<th>Environment</th>
<th>Half-life in day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marine water</td>
<td>&lt; 60</td>
<td></td>
</tr>
<tr>
<td>Fresh or estuarine water</td>
<td>&lt; 40</td>
<td></td>
</tr>
<tr>
<td>Marine sediment</td>
<td>&lt; 180</td>
<td></td>
</tr>
<tr>
<td>Fresh or estuarine sediment</td>
<td>&lt; 120</td>
<td></td>
</tr>
<tr>
<td>Soil</td>
<td>&lt; 120</td>
<td></td>
</tr>
</tbody>
</table>

Microplastics are commonly categorised into (1) primary and (2) secondary types based on its origin. Primary microplastics are intentionally produced for direct use, while secondary ones originate from fragmentation of larger plastic items by usage, waste management or in the environment (Lassen et al., 2015). The main mechanism of primary and secondary sources of microplastics are demonstrated in Table 2 (Sundt et al., 2014).

Table 2 Mechanisms of microplastic pollution

<table>
<thead>
<tr>
<th>Source</th>
<th>Mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Primary</td>
<td>(a) Microplastic intentionally created</td>
</tr>
<tr>
<td></td>
<td>(b) Microplastic as an inherent by product or process</td>
</tr>
<tr>
<td></td>
<td>(c) Unintentional release</td>
</tr>
<tr>
<td>(2) Secondary</td>
<td>(a) Natural fragmenting of macro plastic debris in the sea</td>
</tr>
<tr>
<td></td>
<td>(b) Biological contribution to defragmenting of microplastics</td>
</tr>
<tr>
<td></td>
<td>(c) Remobilization</td>
</tr>
</tbody>
</table>
Effects of microplastics on marine organisms

Sharma and Chatterjee have extensively described the effect of microplastics on marine ecosystem and animal health in their review article, (Sharma & Chatterjee, 2017). A summary is shown in Figure 1. Ingestion of microplastics by certain marine biota can lead to transfer of microplastic to the food chain and inevitably to humans. Effects on human health may be similar to those in animal (Leslie & Depledge, 2020).

![Figure 1 Adverse effects of microplastic on animal health.](image)

Human exposure to microplastics

In 2018, The Guardian reported that microplastics have been found in human stools for the first time ([https://www.theguardian.com/environment/2018/oct/22/microplastics-found-in-human-stools-for-the-first-time](https://www.theguardian.com/environment/2018/oct/22/microplastics-found-in-human-stools-for-the-first-time)). This report was according to a small study which examined eight participants from Europe, Japan and Russia. All of their stool samples were found to contain microplastic particles. The most common plastics found were polypropylene and polyethylene terephthalate. Later in 2019, this study was published in Annals of Internal Medicine Journal (“Detection of Various Microplastics in Human Stool,” 2019). In 2022, studies of microplastics in the faeces of patients with inflammatory bowel disease (IBD) and healthy people revealed that the faecal microplastic concentration in IBD patients (41.8 items/g·dm) was markedly higher than that in healthy people (28.0 items/g·dm). In this work, a total of 15 types of microplastics were detected in faeces, with poly(ethylene terephthalate) (22.3-34.0%) and polyamide (8.9-12.4%) being dominant, and their primary shapes were sheets and fibers, respectively (Yan et al., 2022). Microplastics were also detected in all colectomy samples obtained from 11 adults from Northeastern Peninsular Malaysia in 2020 (Ibrahim et al., 2021). A total of 22 patients suffering from different respiratory diseases were volunteered for sputum samples (a mixture of saliva and mucus coughed up from respiratory tract) to evaluate microplastics in the respiratory tract. The results showed that 21 types of...
Microplastics were identified, and polyurethane was prevalent, followed by polyester, chlorinated polyethylene, and alkyd varnish. Most of the aspirated microplastics detected were smaller than 500 μm in size (Huang et al., 2022).

Microplastics were also found in human placenta (Braun et al., 2021; Ragusa et al., 2021) and meconium (a newborn’s first faeces) (Braun et al., 2021). A pilot study was set up to screen for microplastics with the size above 50 μm in placental tissue and meconium samples during two caesarean sections for breech deliveries (Braun et al., 2021). In this study, human placenta and meconium samples were tested positive for polyethylene, polypropylene, polystyrene, and polyurethane. In the latter study (Ragusa et al., 2021), total of 12 microplastic fragments with the size of 5-10 μm with spheric or irregular shape were found in 4 out of 6 human placentas collected from consenting women with physiological pregnancies. All of the fragments were pigmented; three were identified as stained polypropylene. For the other nine, it was possible to identify only the pigments, which were all used for man-made coatings, paints, adhesives, plasters, finger paints, polymers or cosmetics and personal care products.

Microplastics were also identified in human lung tissues obtained at autopsies. Polymeric particles and fibers were detected in 13 of 20 tissue samples. All polymeric particles were smaller than 5.5 μm in size, and fibers ranged from 8.12-16.8 μm. The most frequently found polymers were polyethylene and polypropylene (Amato-Lourenço et al., 2021). In later years, a higher resolution technique called μFTIR spectroscopy with a size limitation of 3 μm was used to detect and characterize microplastics at any size. In total, 39 microplastics were identified within 11 of the 13 lung tissue samples with an average of 1.42 ± 1.50 particles/g of tissue. Of all the particles detected, 12 polymer types were identified with 23 % of polypropylene, 18% of polyethylene terephthalate and 15% of resin (Jenner et al., 2022).

Recently, on March 24, 2022, a scientific paper on discovery of microplastic particles in human blood was available online (Leslie et al., 2022). The blood samples were taken from 22 anonymized, healthy, non-fasting volunteer adults. Target polymers for analyses were poly(methyl methacrylate), polypropylene, materials containing polymerized styrene, polyethylene and polyethylene terephthalate. The results indicated that 17 out of 22 human blood samples exhibited a quantifiable mass of plastic particles with a size of 700 – 500,000 nm. The key message from this article is that plastic particles from environment may transfer to organs via the bloodstream.

**Human exposure pathways**

Humans are exposed to plastic debris via consumption of seafood and drinking water, contact with food packaging, or inhalation of particles. Annual microplastics consumption, focusing on the American diet, ranges from 39 000 to 52 000 particles depending on age and sex. When inhalation is taken into account, these estimates increase to 74 000 and 121 000. Additionally, individuals who follow their recommended water intake through only bottled drinking water may consume an additional 90 000 microplastics annually, compared to 4 000 microplastics for those who consume only tap water. In the same article, average percent of microplastic particle types including fibers, fragments, granules, film, foam, filaments, and flakes in water, alcohol (beer), indoor air, seafood, salt, sugar, and honey, as shown in Figure 2 (Cox et al., 2019).
Figure 2 Average percent microplastic particle types including fibers, fragments, granules, film, foam, filaments, and flakes in water, alcohol (beer), indoor air, seafood, salt, sugar, and honey.

In another study, it was reported that microplastics have been detected in table salt, drinking water, and air, leading to inevitable human exposure risk (Zhang et al., 2020). This article summarized studies done in 22 countries on microplastics contamination in drinking water including raw and treated water from drinking water treatment plants, tap water and bottled water. Abundance of microplastics in tap water and bottled water is given in Figure 3.

Figure 3 Abundance of microplastics in tap water and bottled water. The results are classified into two categories according to their identification methods: (1) μ-FTIR and (2) μ-Raman or other technologies (dyeing, SEM/EDX).
Human health effects of microplastics

The accumulation of microplastic particles in humans may lead to health risks, e.g., cytotoxicity, hypersensitivity, unwanted immune response, and acute response like hemolysis (the rupture or destruction of red blood cells) (Hwang et al., 2019). Human exposure to microplastics may occur via ingestion, inhalation and dermal contact due to the presence of microplastics in products, food and air. In all biological systems, microplastic exposure may cause particle toxicity, with oxidative stress, inflammatory lesions and increased uptake or translocation. The inability of the immune system to remove synthetic particles may cause chronic inflammation and increase risk of neoplasia (the uncontrolled, abnormal growth of cells or tissues in the body), as presented in Figure 4.

![Figure 4 Possible routes of exposure and toxicity pathways for microplastic debris in human body.](image)

Negative effects of microplastics on organisms health can be divided into (1) physical and (2) chemical effects. The physical effect is related to size, shape, and concentration of microplastics. The chemical effect is related to hazardous chemicals that are associated with microplastics. Microplastics consist of two types of chemicals: (1) additives and polymeric raw materials originating from plastics, e.g., monomers or oligomers and (2) chemical absorbed from the surroundings. (Campanale et al., 2020). One of the well-known additives of concern is bisphenol A (BPA).

BPA is a common plasticizer used in many industries, particularly polycarbonate plastics manufacturing processes and food packaging. BPA is also a chemical component of epoxy resin used in a wide range of building materials. It was reported that several epoxy-based coatings are made of bisphenol A diglycidyl ether (BADGE). BADGE is made of two primary chemicals: (1) BPA and (2) epichlorohydrin (Resins, 2009). It was discovered in the early 1930s that BPA is estrogenic (Glausiusz, 2014). It was confirmed recently by the General Court of the EU that BPA can interrupt hormonal properties on the human body and is associated with obesity, cardiovascular disease, reproductive disorder and breast cancer (Campanale et al., 2020). Moreover, according to a study by National Health and Nutrition Examination Survey (NHANES), BPA residues in urine sample was detected in more than 90% of people in a representative sample of general population in USA. A study in animal proved that BPA caused prostate cancer and alterations in behaviour (Palanza et al., 2002). A study on effect of BPA in human is limited, however, one study raised concerns on miscarriages and other birth defects in human that caused by exposure to BPA (Sugiura-Ogasawara et al., 2005). A summary on health impacts of BPA mainly from epoxy-based coatings, was published in 2009 (Resins, 2009). Laboratory leaching tests performed with approved two-component epoxy-based coatings applied under well-controlled conditions...
indicated generally low but detectable concentration of BPA in the water samples. Field sampling of 27 real tanks indicated that leaching of BPA should not lead to any problem for full-scale tanks with a volume higher than 100 m$^3$ with coating application according to manufacturer’s instructions: curing temperature, curing time and humidity. However, a large-scale examination of 200 pipe section rehabilitated with epoxy coatings during the 1990s in France indicated a significant detection frequency of BPA and BPF with the maximum concentrations of 1 μg/l. It was suggested in this article that rehabilitation of drinking water pipes with epoxy linings should be discontinued (Bruchet et al., 2014).

Despite the fact that there has been limited research done on the effects of microplastics on human health, in addition to scientific articles mentioned above, there are a few articles that has reported in-dept review on toxicity of microplastics to human (Blackburn & Green, 2022; Prata, 2018; Smith et al., 2018).

**Marine paints**

Four main compositions of marine paints are (1) binders, (2) pigments and dyes, (3) solvents and (4) fillers (“Coating Industry (Paints, Lacquers and Varnishes),” 2014). Among all ingredients, binders are the main sources of plastic or polymer in marine paints. Synthetic binders mentioned by Organisation for Economic Co-operation and Development (OECD) are alkyds, acrylics, vinyl, epoxy, urethane and polyester binders. Specialty materials, e.g., silicates and silicones, were also included. Among those, rubber derivatives, alkyd, polyurethane and phenolic resins were reported to be the common used in marine paints.

According to the American Coatings Association (ACA) and US Census Bureau Current Industrial Report MA 325F, marine paints are categorized as special purpose coatings together with automotive refinish and industrial maintenance coatings. Marine paints are divided to four major groups: (1) super-hydrophobic, (2) anti-corrosive, (3) antifouling and (4) foul-release. Details for the last two can be further read in (Verma et al., 2019). Fundamental similarities and differences between plastics and paint were mentioned by turner, (Turner, 2021). Most often used synthetic polymers in consumer and industrial plastics are acrylonitrile butadiene styrene, polyethylene, polypropylene, polyethylene terephthalate (PET), polystyrene and polyvinyl chloride (PVC), while most paints are based on acrylic, alkyd, polyurethane, epoxy or chlorinated rubber binders.

**Microplastic pollution from marine paints**

The main sources of paint fragments in the ocean are normally boats and ships, as well as fixed structures, e.g. pier, oil rig, wind turbine platform. When paint fragments are removed by weathering or wear, they eventually contribute to the microplastic debris in the ocean (Gaylarde et al., 2021). Additionally, the key activities that lead to emission of paint into the environment are surface preparation, e.g., abrasive blasting, coating application and cleaning of paint equipment (OECD SERIES ON EMISSION SCENARIO DOCUMENTS Number 22, 2009).

A report published by United Nations Environment Programme (UNEP) (United Nations Environment Programme, 2021) indicated that marine paints contribute to ocean plastic through direct littering from activities in the oceans (see Figure 5). The main activities that lead to environmental release include (1) surface pre-treatment, (2) coating application and (3) equipment cleaning (OECD SERIES ON EMISSION SCENARIO DOCUMENTS Number 22, 2009).

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Figure 5 Major sources and pathways of human generated plastic waste in the marine environment.

Figure 6 conceptually describes sources of paint particles released into marine environment based on users and applications (Turner, 2021).

Figure 6 Sources of paint particles.

On the global point of view, among all key sources of primary microplastics released into the ocean, which are (1) plastic pellets, (2) synthetic textiles, (3) tyres, (4) road markings, (5) marine paints, (6) personal care products and (7) city dust, marine paints were reported to contributed to 3.7% of global releases of microplastics to the world oceans (Julien and Damien, 2017). Estimates of annual microplastic emissions to European surface waters done in 2018 indicated 400 tonnes contribution from marine paints (Turner, 2021). The most recent published technical report in 2022 indicated contribution of marine paints as high as 7% (Paruta et al., 2022).
Emission factors in percentage for marine paints based on causes estimated by OECD are summarized in Table 3.

**Table 3** Emission factors in percentage for marine paints

<table>
<thead>
<tr>
<th>Cause</th>
<th>Emission Factor (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid coating content spilled directly to the sea during the lifetime of the paint</td>
<td>6</td>
</tr>
<tr>
<td>Coating spilled during painting</td>
<td>1.8</td>
</tr>
<tr>
<td>Weathering of paint during use</td>
<td>1</td>
</tr>
<tr>
<td>Maintenance and abrasive blasting</td>
<td>3.2</td>
</tr>
<tr>
<td>Spreading to soil in the painting area</td>
<td>5</td>
</tr>
</tbody>
</table>

A report on estimation of emission of microplastic from marine paints to marine environment in Norway using double factor provided in Table 3 indicated that discharges to sea and soil from professional maritime paints and recreation boatyards (excluding antifouling paints) are 330 and 400 tonnes per year, respectively (Sundt et al., 2014).

In Denmark (Lassen et al., 2015), emission of ship paints used for recreational boats and professional vessels were estimated to be 5-50 and 16-150 tonnes per year respectively. The estimation was performed with additional criteria to emission factor given in Table 3. It was also mentioned without any further evidence that microplastics from self-polishing antifouling paints may further contribute to the estimated total emissions.

In Sweden (Magnusson et al., 2016), emission of microplastics from marine paints used on leisure boats using emission factors provided Table 3 were estimated at 110-550 tonnes per year from coatings and 6-139 tonnes per year from antifouling paint. In the case of commercial vessels, emission of microplastics from marine paints estimated using emission factors provided by OECD were 40 tonnes per year from coatings and 2-8 tonnes per year from antifouling paint. With the help of available emission factors and assumptions on the use of coatings and antifouling paints, the total annual emissions of microplastics from boat hulls, both commercial and leisure boats, in Sweden may fall in the range of 158-737 tons directly to aquatic environment.

Another study published in 2017 reported that 21 surface water samples were collected in areas close to Stockholm city, Nynäshamn, Trosa and Himmerfjärdsverket. Paint flakes were found only in the water samples collected from Stockholm city and Trosa, where the latter were mentioned to a town with large leisure boat activity (Gewert et al., 2017). **Figure 7** gives example of photograph of retrieved plastics from samples collected from Stockholm city with the most abundance plastic flakes.

**Figure 7** Photograph of retrieved plastic debris from water samples collected from Stockholm city.
A study done on estimation of emission of microplastic from marine paint was done in Netherland with the focus only on the ship hull, where other parts of the ship were not considered in the calculation (Verschoor et al., 2016). Moreover, emission of microplastics during the use of the ships were also estimated. The results indicated that the total microplastic emission to soil and water from the paints in the shipping sector is approximately 200 tons/year.

During October 2016 and 2017, 24 water samples from 24 locations were collected from the German Bight with 2.5 m depth (Dibke et al., 2021). These locations were selected to include different potential of microplastic sources, e.g., high shipping traffic, vicinity to high tourist activities. The results indicated that, after filtration, all collected particles were smaller than 1 mm in size and seven plastic types were detected as shown in Figure 8. From both year, PMMA and PVC are the most abundance polymer types and indicated signal related to marine activities. In central and estuarine areas, marine/antifouling paint related particles, i.e., abraded chlorinated rubber-, acryl-styrene-, and epoxy binder-containing particles were observed. The authors suggested such particles as the main microplastic source, indicating ship “skid marks”.

![Figure 8](image1.png)


Paint flakes were found to contribute to anthropogenic microlitter in the Baltic Sea water column by collecting water samples using cruises in 2015-2016 in the Bornholm, Gdansk, and Gotland basins at the depth range form 0-217.5 m (Bagaev et al., 2018). Microplastic particles collected were in the size range of 0.5-5 mm. Figure 9 shows an example of paint flake found and describes percentage of the three main particle types collected.
Another study collected plastic debris in ocean surface waters of the Antarctic Peninsula (Lacerda et al., 2019). Hard and flexible fragments, spheres and lines, in nine colors, composed mostly of polyurethane, polyamide, and polyethylene were found. Paint fragments were presented at all sampling points and were approximately 30 times more abundant than plastics. Figure 10 shows appearance of paint flakes collected around the Antarctic Peninsula in this study.

Figure 10 General appearance of paint flakes collected around the Antarctic Peninsula.

In another work, non-fibrous microplastics in the North Atlantic Ocean during 2018 were collected (Turner et al., 2022). Concentration of the particles found was reported to be approximately 0.01 particle/m$^3$. Among the samples analysis, all except one were identified as paint flakes from boat paint, non-antifouling, antifouling and building paint. It was mentioned in this article that after fibres, paint flakes appear to be the most abundant type of microplastic in the North Atlantic Ocean.

**Characterization of microplastics**

Separation methods for microplastic debris includes (1) density separation, (2) filtration, (3) sieving and (4) visual sorting (Hidalgo-Ruz et al., 2012). The most common analytical technique to identify chemical composition of microplastics is infrared (IR) spectroscopy.
Higher resolution of this technique have also been reported in (Cutroneo et al., 2020) and listed as follows:

- Fourier-transform infrared spectroscopy (FTIR)
- Micro-Fourier transform infrared spectroscopy (Micro-FTIR)
- Attenuated total reflection Fourier transform infrared spectroscopy (ATR-FTIR)
- Micro-attenuated total reflection Fourier transform infrared spectroscopy (Micro ATR-FTIR)
- Fourier Transform Near-Infrared spectroscopy (FT-NIR)
- Raman spectroscopy
- Micro-Raman spectroscopy
- Semi-automated micro-Raman spectroscopy
- Near Infrared Spectroscopy (NIR)
- Differential scanning calorimetry (DSC)

Pyrolysis Gas Chromatography-Mass Spectrometry (Py-GC/MS) was also reported for characterization of microplastics (Dibke et al., 2021), where the results show that microplastics sampling from the German Bight composed of PET, PP, PE (most commonly found in plastic packaging), PVC, PC and PMMA (most commonly found in ship paints).

The most recently published scientific article addressed challenges in analysis of microplastics due to, for instance, broad size range (Ivleva, 2021). Techniques used for analysis of microplastics were extensively described and categorized, i.e., (1) mass-based methods, (2) particle-based methods and (3) combination of the two. Figure 11 shows examples of FTIR spectra of certain common plastic polymers.

**Figure 11** FTIR spectra of certain common polymers. PVC stands for polyvinyl chloride.
Research and development

Marine paints contribute to microplastic pollution mostly unintentionally, either due to weathering or incidents during application, maintenance and disposal (Julien and Damien, 2017). Paints used for marine application can be damaged or degraded due to several factors, e.g., solar radiation, high salinity, temperature fluctuation, wet-dry cycles, mechanical friction, macro and micro living species (Song and Feng, 2020). Such processes alter both physical and chemical properties of the paints and most often lead to generation of secondary microplastics (Simon et al., 2021). An epoxy amine-based seawater coating was characterized after 18 years of exposure during service (Iannarelli et al., 2022). Morphological changes in the pigments and binder in the near surface area were evidently observed and assume to be a result of temperature variation which create stress within the coating.

The use of nontoxic and eco-friendly natural raw materials which do not exhibit any adverse effect on the environment upon application for marine paints has been a focus for research in this area (Kyei et al., 2020). Natural materials mean eco-friendly, biodegradable and cost-effective throughout the value chain. Biodegradable polymers can be originated from two sources, i.e., natural/renewable and synthetic.

Biodegradable polymers and butanolide (derived from marine bacteria) were used in antifouling coatings to replace conventional polymers and biocides, respectively. The results demonstrated that such system exhibited good antifouling ability for longer than three months, and the polymer degraded in seawater with increasing degradation rate in the presence of marine organisms or enzymes (Ma et al., 2017).

A bio-based amphiphilic hydrogel coating were prepared with combination of hydrophobic bio-based epoxy and hydrophilic nanosilver hydrogel networks exhibited antifouling and mechanical properties (Lu et al., 2021). The hydrophobic network was bio-based epoxy monomer containing siloxane chain synthesized from bioresource eugenol and crosslinked by isophoronediamine. The hydrophilic network was a mercapto hydrophilic polymer synthesized and combined with trifluoromethanesulfonic acid silver salt. The coated panels (stainless steels) were field tested in marine environment for 45 days and 5 months and the results indicated no damage or flaking of the coated surfaces.

A wide variety of resins was reported to be synthesized from Cashew Nut Shell Liquid (CNSL), e.g., polyesters, phenolic resins, epoxy resins, polyurethanes, acrylics, vinyl, alkyds (Balgude and Sabnis, 2014). Addition of biodegradable poly ε-caprolactone (PCL) and poly butylene succinate (PBS) in marine anti-biofouling was reported to demonstrated good anti-biofouling performance when applied on glass fiber reinforced epoxy resin panels (Chen et al., 2016). An organic antifoulant used was 4,5-dichloro-2-octyl-isothiazolone (DCOIT). The tests were done in seawater (temperature range of 25-28 °C and salinity of 35%) at a depth of 1 m for four months. Photographs of tested panels are presented in Figure 12.
In many countries in EU, e.g., Denmark, the Netherlands, initiatives regarding reduction of microplastic emissions have been started both at national and international levels. In Sweden, according to this report, Swedish Environmental Protection Agency (Naturvårdsverket in Swedish) and Swedish Environmental Research Institute (IVL Svenska Miljöinstitutet in Swedish) are actively working on microplastics in the environment. However, the most recent published report on Microplastics in the Environment 2019 by Naturvårdsverket only focused on artificial grass pitches and textile laundry as sources of microplastics (The Swedish Environmental Protection Agency, 2021). The work done on emission of microplastics from marine paints by IVL Svenska Miljöinstitutet addressed the uncertainty of the evaluation due to limited access to data (Magnusson et al., 2016). A group of researchers at Materials and Production Division at RISE - Research Institutes of Sweden have been working on microplastic releases from industrial laundries (Brodin et al., 2018).

Due to the current literature review, examples of proposed research topics and its possible output to help mitigate emission of microplastics from marine paints to environment are listed in Table 4.

Table 4 Proposed research area according to the actions needed to be taken

<table>
<thead>
<tr>
<th>Needed action</th>
<th>Research area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identification of paint fragments in European water</td>
<td>Systematic sampling and characterization of microplastic debris from European water</td>
</tr>
<tr>
<td>Research efforts on paint that can be biodegraded once it become microplastic litter</td>
<td>Biodegradable polymers for marine paints</td>
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<tr>
<td>Research efforts on plastic free paints with adequate anticorrosion/antifouling protection</td>
<td>Development of inorganic paints</td>
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<tr>
<td>Research efforts to replace toxic, bio-accumulable materials from marine paint formulations</td>
<td>Development of paint formulations for marine paints</td>
</tr>
</tbody>
</table>
Reference


A dose of bisphenol A during fetal life or in adulthood alters maternal behavior in mice. *Environmental Health Perspectives, 110*(SUPPL. 3), 415–422. https://doi.org/10.1289/ehp.02110s3415


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