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Potential microplastic release from the maritime industry: Abrasion of rope

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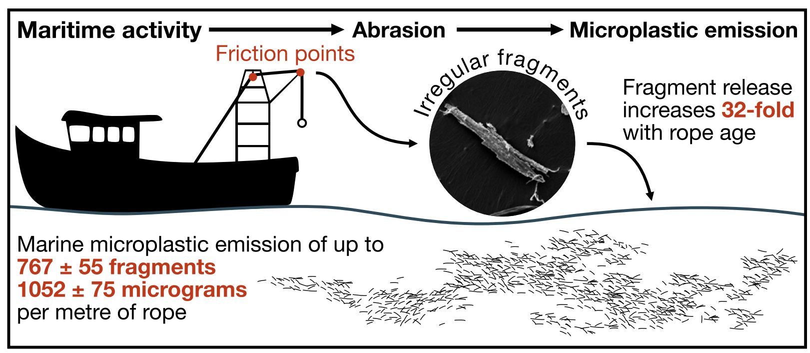
HIGHLIGHTS

- This study tested a variety of ropes differing in age and polymer type.
- Microplastic from rope abrasion is likely to directly enter the marine environment.
- Microplastic fragments, not fibres, were generated from rope wear.
- New rope released significantly less microplastic fragments than older rope (≥ 2 yrs).
- Need for standards on rope maintenance, replacement and recycling.

GRAPHICAL ABSTRACT



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ABSTRACT

While land-based sources of plastic pollution have gained increasing attention in recent years, ocean-based sources have been less well studied. The aim of this study was to compare a variety of ropes (differing in age, wear surface and material) to quantify and characterise the production of microplastic during use. This was achieved by simulating, in laboratory and field experiments, rope hauling activity which is typically performed on board maritime vessels, such as fishing boats. Microplastic generation was quantified by collecting fragments that were released as a consequence of abrasion. Notably, we show that microplastic fragments generated from rope wear during use were characteristically irregular in shape, rather than fibrous such as those assigned to synthetic rope by previous studies. Therefore, we suggest that some of the plastic fragments found in the marine environment may have been falsely attributed to land-based sources but have in fact arisen form the abrasion of rope. Our research found that new and one-year old polypropylene rope released significantly fewer microplastic fragments (14 ± 3 and 22 ± 5) and less microplastic mass (11 ± 2 and 12 ± 3 μg) per metre hauled compared to ropes of two (720 ± 51, 247 ± 18 μg) or ten (767 ± 55, 1052 ± 75 μg) years of age. We show that a substantial amount of microplastic contamination is likely to directly enter the marine environment due to in situ rope abrasion and that rope age is an important factor influencing microplastic release. Our research suggests the need for standards on rope maintenance, replacement, and recycling along with innovation in synthetic rope design with the aim to reduce microplastic emission.

1. Introduction

The accumulation of plastic in the marine environment is a rapidly growing, global environmental issue. Over 360 million tons of plastic are made every year, with an estimated 8 million tonnes of plastic entering the world's oceans annually (Jambeck et al., 2015;

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PlasticsEurope, 2019). The majority of marine plastic debris originates from land-based sources (>80%) (Derraik, 2002; Faris and Hart, 1995; Jambeck et al., 2015). However, plastic can also be released from ocean-based sources such as fishing activity, shipping and aquaculture (Andrady, 2011; GESAMP, 2015).

Historically, maritime rope and netting have been produced from natural resources such as cotton, flax or hemp fibres (Sahrhage et al., 1992). Following the large-scale increase in plastic production during the 1950s, synthetic gear has progressively replaced its natural counterparts. That is because plastic is less expensive and has higher tensile strength as well as greater resistance to rotting than natural materials (Coles, 2009; Deroiné et al., 2019; Terry and Slater, 1998). Currently, fishing gear, including netting, long lines, pots and trawls, is made from plastics of varying polymer types.

There is evidence that fish ingest fishing gear. Saturno et al. (2020) examined 216 gastrointestinal tracts of Atlantic cod (*Gadus morhua*) caught by commercial fishers at Fogo Island, Newfoundland and Labrador, Canada. Their study found two gastrointestinal tracts which contained intact bait bags (used in commercial pots) and the third tract contained a polypropylene thread, likely originating from fishing rope. It has also been suggested that a substantial proportion of the microplastic filaments retrieved from the digestive tracts of dissected organisms (Devriese et al., 2015; Nadal et al., 2016) could have originated from maritime gear.

All ropes may be subject to wear due to abrasion during use (Terry and Slater, 1998). Despite careful consideration of numerous parameters, including rope strength, elasticity, energy absorption and abrasion resistance by the maritime industry (Sharp, 1976), synthetic plastic is susceptible to embrittlement, cracking and reduction in mechanical properties. This can lead to fragmentation and the formation of secondary microplastic fibres (Arthur et al., 2009), and concerns about associated marine contamination (Buchanan, 1971). Abrasion of synthetic ropes can occur both internally (contact between yarns of the same rope) and externally (contact between rope and another surface) (Mandell, 1987). Both types of abrasion occur during hauling, since yarn-to-yarn friction increases as the rope is strained and becomes compact (Terry and Slater, 1998).

Most industrial fishing vessels are equipped with hydraulic net haulers or net drums, the usage of which may cause considerable abrasion and could result in the direct release of microplastic into the marine environment. Although rope has been reported as a prevalent type of macro litter in the marine environment (Nelms et al., 2017), there are currently no peer-reviewed publications which address its fragmentation into microplastic during use. Therefore, the aim of this study was to test a variety of different ropes (differing in age, diameter and material) to quantify and characterise the production of secondary microplastic. This was achieved by simulating mechanical rope hauling activity, which is typically performed on board maritime vessels, in laboratory and field experiments. Microplastic generation was then quantified by collecting fragments that were released as a consequence of abrasion.

2. Materials and methods

2.1. Rope categories

Secondary microplastic generation from the use of maritime rope was compared between six ropes of different ages, diameters and materials (Table 1). These were selected to represent a range of different rope types and ages. Additionally, they were chosen based on what was available from industry. The ropes were new, one, two or ten years old and 12 or 16 mm in diameter (corresponding to an approximate wear surface of 377 or 503 cm^2 m^{-1}). The three ropes classified as aged had been used for fishing, hauling or mooring and were deemed to be at the end of their life service by their previous owners. Polypropylene (PP) was the most common polymer type, with representative ropes of all ages and diameters, while polysteel was only tested new. Polysteel rope is a mixture of polyethylene (PE) and PP, a common choice for commercial fishing (personal communication with fishermen and retailers). All ropes were obtained from local retailers or fishermen in Plymouth (UK) who provided information on previous use. Polymer type was confirmed by FTIR microscopy in transmission mode with a Hyperion 1000 microscope coupled to a Vertex 70 spectrometer (Bruker). For each sample, the spectrum was recorded with 32 scans between 4000 and 600 wavenumbers cm^{-1}. The spectra obtained were compared against a spectral database of synthetic polymers (BPAD polymer & synthetic fibres ATR).

Table 1
Rope samples and their properties.

Age (yr)	Diameter (mm)	Wear surface (cm^2 m^{-1})	Density (g cm^{-3})	Polymer	Previous use
0	12	377	0.95	Polysteel	None
0	16	503	0.95	Polysteel	None
0	16	503	0.91	Polypropylene	None
1	12	377	0.91	Polypropylene	Buoy line for nets
2	16	503	0.91	Polypropylene	Hauling line
10	12	377	0.91	Polypropylene	Mooring line (stored exposed outside)

2.2. Field experiment

Rope fragmentation was tested with the ropes being pulled by a hauler on a rig setup on a boat to obtain characterisation of microplastics produced in situ, and a constructed hauler in a laboratory to estimate abundance of microplastic shedding. The University of Plymouth's research vessel *Falcon Spirit* was used to confirm microplastic generation from the different ropes while at sea. Mechanical hauling was undertaken in water depths of 10 m, where 15 m from each rope hauled up a 15-kg weight ($n = 3$). As the rope being hauled was wet, wide funnels were placed at two different friction points (Fig. 1a). Microplastic was collected together with seawater via funnels into a metal bucket and then transferred into glass vials. To obtain the microplastic particles from this water, each sample was vacuum filtered over Whatman glass-filter paper (1.6 μm), then dried at 30 °C until at a constant dry weight. Once dry, whole particles and their topography were visualised by scanning electron microscopy (JEOL, 7001F) imaging. This step was used to confirm microplastic shedding from ropes during practical use within the environment.

2.3. Laboratory experiment

A dry laboratory setup was designed to quantify shed fragments from rope after confirmation of rope shedding obtained on the research vessel (Fig. 1b). This was necessary as the wet rope from the boat experiment also captured other particulates such as natural sediment grains which affected mass abundance estimates. In the laboratory study, each replicate ($n = 5$) comprised 50 1-m hauls of a 2.5-kg weight by hand on an untested section of rope. Microplastic, fragmented from the main structure of the rope through abrasion, was collected onto a plexiglass sheet underneath two pulleys (Fig. 1b). Microplastic was collected from only the first two pulleys to reproduce the setup on the research vessel. These were then brushed into a glass vial, using a goat hairbrush and a glass funnel. If any of the ropes had previously been used for maritime activities, sand or non-plastic materials were extracted and separated from collected microplastic using Endecotts woven wire sieves of varying mesh size. The mass of the collected microplastic from rope was weighed with an analytical balance (Precisa 2200C). Mass released per hauled metre of rope (g m^{-1}) was calculated by dividing the measured mass by 50.

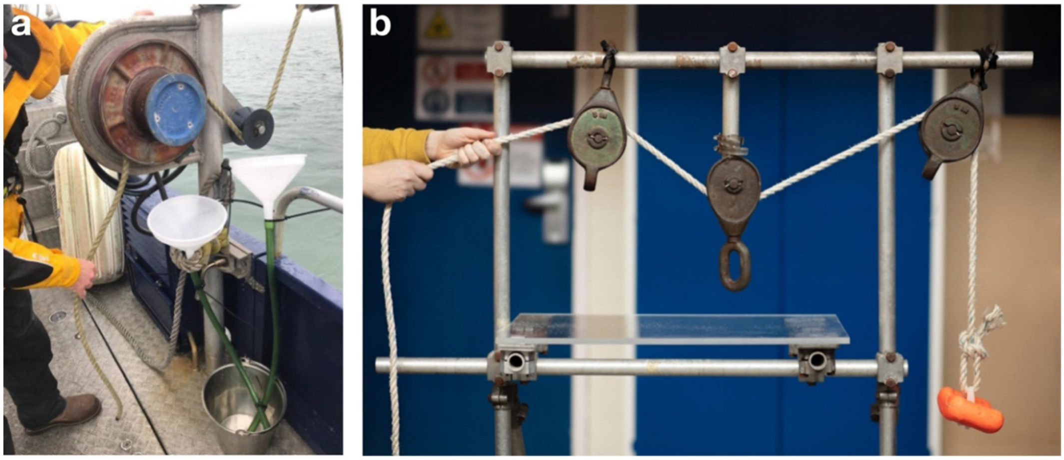

Fig. 1. Experimental setup to collect microplastic fragments from rope hauling activity. **a**, Field experiment on board the research vessel *Falcon Spirit*. **b**, Dry laboratory experiment. Microplastic released at the two friction points (pulleys) was collected in a bucket via funnels (**a**) or on a plexiglass sheet (**b**).

For Quality Assurance and Quality Control, during any laboratory analysis, all steps were conducted in a controlled access laboratory. The testing area was cleaned before and after rope hauling and non-plastic items were used at all times (apart from the plexiglass sheet to capture fragments released from ropes). Cotton laboratory coats and clothes were worn to reduce contamination from synthetic textiles. However, due to the mass being collected from hauling, it was considered that airborne microplastic contamination would be negligible.

2.4. Microplastic fragment quantification

To quantify the number of fragments from the collected microplastic mass, a Malvern Mastersizer 2000 laser particle sizer (MM2) was used to measure the size-frequency distributions (SFDs) of the collected microplastics extracted using the dry rig setup. The resultant particle size distributions were obtained from an average of 25 measurements per rope. The instrument assumes that the particles are spherical in shape. However, as the microplastics produced were typically of cuboid shape, three prominent peaks were observed which corresponded to the length, height and width of the microplastic particle. This allowed the calculation of fragment volume (cm^3). Together with the density ($g\ cm^{-3}$) of each rope and the measured microplastic mass ($g\ m^{-1}$), the number of microplastic fragments per hauled metre of rope (N) was then calculated as

$$N = \frac{M}{D \times V}$$

where M is the microplastic mass ($g\ m^{-1}$), D is the rope density ($g\ cm^{-3}$) and V is the average fragment volume (cm^3).

2.5. Data analysis and visualisation

Data analysis and visualisation were performed in R v4.0.2 (R Core Team, 2020) within the integrated development environment RStudio v1.3.1093 (RStudio Team, 2020). Data exploration revealed strong heterogeneity, despite the assumptions of normality being met. Therefore, heterogeneity was modelled using generalised least squares implemented in the R package *nlme* v3.1-151 (Pinheiro et al., 2020). We report X^2 test statistics as well as *t* ratios (mean effect size ÷ standard error of the effect size) when there is more than one contrast. Descriptive statistics were subsequently calculated with *psych* v2.0.12 (Revelle, 2020) and visualised with *ggplot2* v3.3.3 (Wickham, 2016).

3. Results

Microplastics generated by hauling on the research vessel and in the laboratory set up were found to be irregularly shaped and fragmented rather than fibrous (Fig. 2a, b). On closer inspection of fragment topography, there were visible cracks indicating the microplastic pieces were potentially susceptible to further breakdown into smaller parts (Fig. 2c). The size of the fragments between all rope types typically ranged between 500 and 1000 μm.

Abrasion of microplastic is likely determined by various factors. The effect of wear surface (diameter × π × length) was tested with two new polysteel ropes of different diameter (12 and 16 mm, corresponding to 377 and 503 $cm^2\ m^{-1}$ wear surface) (Table 1). It was found that the rope with 25% smaller wear surface released 37% more microplastic fragments (mean ± s.e.m.: 46.17 ± 1.56 vs. 33.8 ± 4.51 m^{-1}, $X^2_{1,10} = 6.72$, $p = 0.01$, Fig. 3a) and 63% more microplastic mass (16.56 ± 0.56 vs. 10.16 ± 1.36 $\mu g\ m^{-1}$, $X^2_{1,10} = 19.04$, $p < 0.001$, Fig. 3b). Due to equal

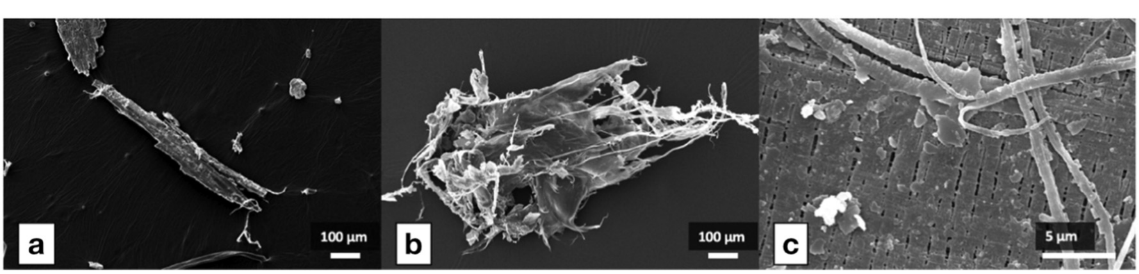

Fig. 2. Scanning electron microscopy images of a microplastic fragments produced by rope abrasion. **a**, New 16-mm polysteel rope (200× magnification). **b**, One-year old 12-mm polypropylene rope (200 × magnification). **c**, Cracks in the topography of ten-year old 12-mm polypropylene rope (5000× magnification). Images were taken at Plymouth Electron Microscopy Centre.

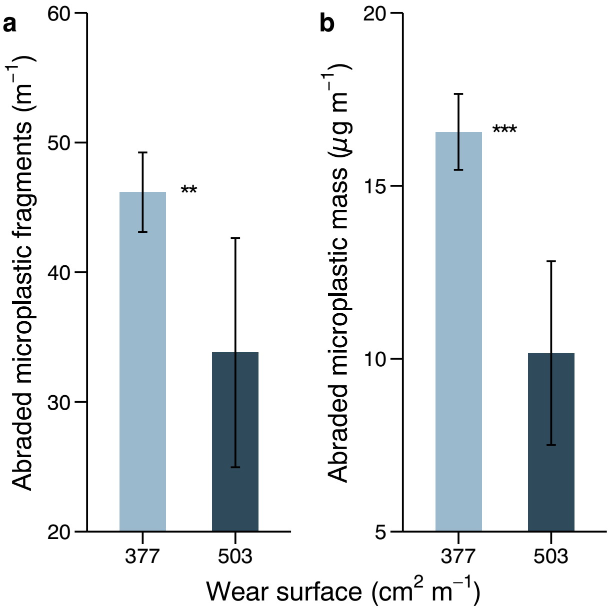

Fig. 3. Number (**a**) and mass (**b**) of microplastic fragments released through abrasion from new polysteel rope of different wear surfaces (derived from rope diameter) per hauled metre with a load of 2.5 kg. Bars are means and error bars are 95% confidence intervals ($n = 5$). Asterisks indicate the significance of each contrast: $p < 0.01$ **, $p < 0.001$ ***.

and haphazard representation of 12- and 16-mm diameter ropes across ages (Table 1), wear surface was removed as an explanatory variable from the subsequent analysis. The specific uses of each rope were similarly assumed to have little influence on the effect of rope age on microplastic release.

Focussing on the explanatory variables of interest, we found effects of rope age and material on released number ($X^2_{4,\ 30} = 404.78$, $p < 0.001$) and mass ($X^2_{4,\ 30} = 369.78$, $p < 0.001$) of microplastic fragments. New polysteel rope released 176% more microplastic fragments than new polypropylene rope (39.99 ± 3.05 vs. 14.47 ± 2.76 m^{-1}, $t = 6.2$, $p < 0.001$, Fig. 4a). However, no such trend was evident for microplastic mass (13.36 ± 1.27 vs. 10.8 ± 2.06 μg m^{-1}, $t = 1.06$, $p = 0.3$, Fig. 4b). This suggests that polymer type may have some effect on microplastic emission from synthetic rope. The discrepancy between the results for number and mass of fragments is due to the 56% smaller fragment mass of polysteel rope.

With 22.46 ± 5.39 fragments m^{-1} and 11.6 ± 2.79 μg m^{-1}, one-year old polypropylene rope did not release more microplastic fragments ($t = 1.32$, $p = 0.2$, Fig. 4a) and mass ($t = 0.23$, $p = 0.82$, Fig. 4b) than new polypropylene rope. However, at a rope age of two years, a threshold was reached and emission increased to 719.72 ± 51.49 pieces and 246.6 ± 17.64 μg of microplastic per hauled metre of rope. This level of fragment and mass generation was 31 times ($t = 13.47$, $p < 0.001$, Fig. 4a) and 20 times ($t = 13.16$, $p < 0.001$, Fig. 4b) higher than that of one-year old rope respectively. While microplastic fragment release did not increase further in ten-year old rope (767.39 ± 54.52 m^{-1}, $t = 0.64$, $p = 0.53$, Fig. 4a), the abraded microplastic mass tripled compared to two-year old rope (1051.89 ± 74.74 μg m^{-1}, $t = 10.49$, $p < 0.001$, Fig. 4b). This discrepancy between the effect of rope age on fragment and mass release was due to the three times higher fragment mass in ten-year than two-year old polypropylene rope.

4. Discussion

The results of this study are the first to indicate that large quantities of microplastic can be formed from mechanical hauling of ropes in maritime settings. To put the results into perspective, in fishing activities depending on the vessel and the depth at which fishing takes place, rope length deployed could be up to 220 m (Galbraith et al., 2004). Assuming a modest 50 m of rope is being hauled in from a boat, we predict that each time rope less two-year old rope is hauled in it could release 700–2000 microplastic pieces, while rope two or more years old could emit 36,000–38,000. Moreover, with 4500 active fishing vessels in the UK which can spend 100 active days at sea (Moran et al., 2019), collectively this could result in 326 million to 17 billion microplastic pieces entering the ocean annually. Our results therefore indicate that the maritime sector could be a significant source of microplastic to the marine environment. These estimates were calculated after hauling a 2.5 kg weight. Most maritime activities would be hauling up much heavier loads, creating more friction and potentially more fragments. Hence our estimates are likely conservative. Similarly, Welden and Cowie (2016) assessed the fragmentation of PP, PE, and nylon rope. They consequently estimated that 47,616 t of microplastic would be produced annually from the degradation abandoned, lost, discarded fishing gear (ALDFG). However, this estimate did not account for microplastic

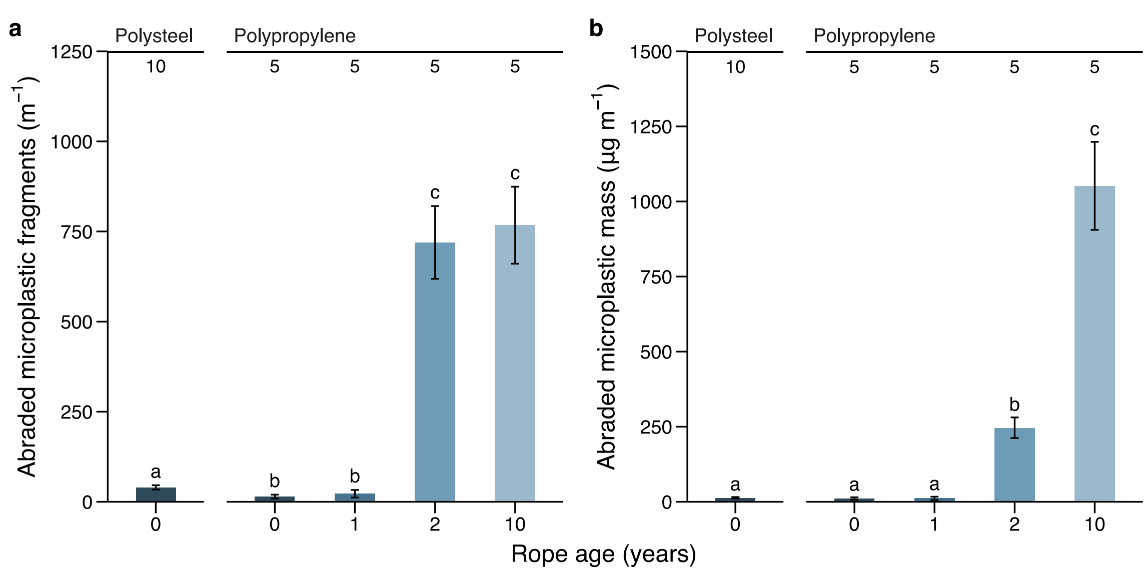

Fig. 4. Number (**a**) and mass (**b**) of microplastic fragments released through abrasion from polysteel and polypropylene rope per hauled metre with a load of 2.5 kg. Bars are means and error bars are 95% confidence intervals. Numbers are group sample sizes. Letters indicate groups of statistical similarity at the 95% confidence level.

production resulting from fragmentation and wear through abrasion during use.

We show that new ropes release fewer microplastic fragments per metre hauled than ropes that are at least two years old. Marine ropes can be degraded by salt (Terry and Slater, 1998). Therefore, it is likely as a consequence of environmental degradation that the greatest mass of microplastic was shed by the oldest rope, which had spent the longest time in service and therefore had been exposed to UV and saltwater the longest. In comparison, research by Song et al. (2017) tested passive and active degradation of PE and PP pellets by exposing them to UV for up to one year and mechanically abrading them with sand for two months, respectively. They found that PE and PP were more susceptible to fragmentation by mechanical abrasion with the presence of UV.

We suggest that differences in rope type and age, with equal exposure to UV and saltwater, influence microplastic generation. In the maritime industry, rope replacement varies according to the type of rope and usage. Nonetheless, ropes are typically replaced every year or discarded after visual inspection. Presently, there are no standards enforcing when ropes and lines should be replaced, but there are recommendations. Typically, ropes are stored away from heat and sunlight, if possible, in a separate compartment which is dry and well ventilated, away from containers of chemicals, detergents, rust removers, paint strippers and other substances capable of damaging them. Rope should be inspected internally and externally before use for signs of deterioration, undue wear or damage (MCA, 2010). Further means of minimising abrasion and environmental degradation include applying marine coatings and resins, avoiding pinching when hauling by ensuring the diameter of the pulley groove is 10% greater than the rope diameter and increasing the lubricity of the fibres within the rope (Terry and Slater, 1998). Rope users should ensure that rope diameter is sufficient during purchase and maintenance. Rope construction is also key, considering that braided ropes are more sensitive to abrasion than twisted ropes (Terry and Slater, 1998).

Notably, we also show that microplastics generated from rope wear during use were characteristically damaged, irregular fragments rather than fibres which had previously been described in the environment (De Witte et al., 2014; Devriese et al., 2015; Nadal et al., 2016). This suggests that previous studies discussing fibrous microplastic originating from the wear of maritime gear (e.g. Baalkhuyur et al., 2020; Buchanan, 1971; Saturno et al., 2020) are not accounting for microplastic from maritime rope hauling due to their distinctly differing physical characteristics, and that fragments generated in this manner have not previously been attributed to this source. More work would be needed to establish how the dimensions of these fragments might vary with different rope types and duration of use.

While there has been growing attention around ALDFG as a contributor to macroplastic pollution, our research suggests that the generation of microplastics from direct use in fishing and other maritime activities is also a cause for concern. Our study is the first to show that a substantial amount of microplastic pollution is directly entering the marine environment due to rope abrasion. It also provides evidence that, contrary to expectation, such microplastic is not fibrous but fragmented (Fig. 2). This indicates that similar fragments, which have been found in the marine environment, have perhaps not been attributed to the correct source. Lastly, with newer rope typically shedding less microplastic, our research calls for potential guidelines on rope design, maintenance and replacement with systems in place to allow older ropes to be recycled. Further work is required to identify best practices.

Data and code availability

All data and code are stored in the open-access repository at github.com/lukaseamus/marine-microplastic. We place no restrictions on data and code availability.

CRediT authorship contribution statement

I.E.N., A.C·B and R.C.T. designed the study. I.E.N. collected data and analysed data. A.C·B. provided technical input. L.S.W. analysed and visualised data. I.E.N. wrote the first draft of the manuscript. I.E.N., L.S.W. and R.C.T. edited the manuscript and all authors approved on the final draft.

Declaration of competing interest

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