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Reducing plastic pollution caused by demersal fisheries

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ABSTRACT

Marine microplastics generated by wear and tear of bottom trawls and demersal seines during their service life is a growing environmental concern that requires immediate attention. In Norway, these fishing gears account for more than 70 % of the landings of demersal fish species, but they are also the leading sources of microplastics generated by fisheries. Because these two fishing gears are widely used around the world, replacing fossil-based non-degradable plastics with more abrasion-resistant materials, including biodegradable polymers, should contribute to the reduction of marine litter and its associated environmental impacts. However, the lack of available recycling techniques and the need for separate collection of biodegradable polymers means that these materials will most likely be incinerated for energy recovery, which is not favourable from a circular economy perspective. Nonetheless, from an environmental perspective the use of such biodegradable polymers in demersal fisheries could still be a better alternative to standard polymer materials.

1. Introduction

Marine plastic litter contributes 60–80 % of the total marine debris around the globe (Moore, 2008; UN, 2021). The annual influx of plastic waste in the ocean is estimated to be 4.8–12.7 million metric tonnes (MT) (Jambeck et al., 2015; Giskes et al., 2022), of which 18–20 % is generated through marine activities. Globally, the fishing and aquaculture industry emits a large amount of plastic litter (Boucher and Billard, 2019). The OSPAR Commission (2020) estimated that 17 % of marine litter found in the Northeast Atlantic region is caused by the fisheries and aquaculture industries. Marine litter, especially that related to microplastics (MPs) and ghost fishing, has serious impacts on the marine environment (FAO, 2016; Napper and Thompson, 2020; Gilman et al., 2021). The formation of MPs is often caused by abrasion of plastics or fragmentation during degradation due to weathering. Microplastic particles can be ingested by plankton and filter-feeding organisms and subsequently enter the marine food chain (Lusher et al., 2017; Alberghini et al., 2023). Abandoned, lost, and discarded fishing gears (ALDFGs) have drastic economic consequences, one of which is the decimation of fish stocks through ghost fishing (Deshpande and Aspen, 2018).

Bottom trawling and demersal seining are known contributors to marine litter and MPs, and they have a high gear-specific relative risk of generating plastic waste (Syversen et al., 2022). Use of bottom trawls and their gear components, especially dolly ropes, has been debated and researched for many years (OSPAR, 2021). Dolly ropes are used to protect the trawl netting from wear and tear caused by contact with the seabed (Fig. 1). Their use is common among several types of demersal fisheries around the world, but they are mainly found in Europe around the North Sea, English Channel, Irish Sea, Bay of Biscay, and in Arctic areas of the Barents Sea (DollyRopeFree, 2018; OSPAR, 2021). Dolly rope frays easily, and OSPAR (2021) estimated that at least 25 MT of dolly rope threads end up in the North Sea annually, and a similar amount may be cast overboard during maintenance work. Norwegian trawlers generate an estimated 40 MT of dolly rope particles every year (Martinussen, 2021), and worldwide fisheries produce even more (Syversen et al., 2022).

Demersal seining (Fig. 2) is commonly practiced in Europe,

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especially in Denmark (anchor seining) and Scotland (fly dragging) (Grimaldo et al., 2010), and it is the second most used fishing gear to harvest demersal fish species in Norway. Syversen et al. (2022) estimated that seine ropes, of which combination ropes (steel core with polyethylene (PE)/polypropylene (PP) cover) are most common, lose 20–30 % of their plastic mass every season (lasting for approximately 6 months) due to wear and tear. In Norway, this results in 80–100 MT of plastic waste annually by demersal seine fisheries; globally, more than 300 MT of MPs are produced each year by this gear (Syversen et al., 2022). Currently, Norway has no viable final disposal solutions for these types of plastic waste.

In Norway, the collection of discarded fishing gears faces several challenges. Large distances between waste facilities that receive fishing and aquaculture plastic leads to high transport costs (Vangelsten et al., 2019). Currently, no regular practice is associated with either EOL gear or ALDFG in Norway and the European Union. Nofir AS[2] (2016) stated that 76 % of their total input of fish nets is recycled, 2 % is reused, and 22 % ends up as waste. During the recycling process, fishing nets and ropes are first washed by physically removing any organic matter, and then the nets are stripped using serrated knives and separated into PP, PE, and nylon polyamide (PA) fractions. The PP and PE fractions are mechanically recycled, and the PA fractions are chemically recycled. The mechanical recycling process produces granules as a product, and chemical recycling or depolymerization converts PA6 polymer chains into Caprolactam (Hirschberg and Rodrigue, 2023). Brodbeck (2016) identified key barriers associated with different EOL treatments, which include EOL gear treatment options, recycling/reuse support mechanisms, and prevention mechanisms for lost and abandoned gear in the sea. Fig. 3 provides an overview of these barriers and mechanisms.

The preferred option should be recycling or reuse, but material quality is a challenge. Additionally, PE is a low-value material (Nofir, 2016). Strict anti-fouling and waste regulations can also create a barrier to recycling. Examples of these waste regulations are high landfill tax, high transport costs, gear must be thoroughly washed to comply with Norwegian antifouling regulations and must be separated/sorted manually, which is time intensive (Brodbeck, 2016). At present, recycling opportunities for plastics from both fisheries and aquaculture are limited and are often complicated by both the number of different plastics used and the anti-fouling coatings on nets and mooring gear. Standard PE/PP Danline demersal seine ropes with steel core and PE/PP/polyethylene terephthalate (PET) dolly ropes are fishing gears made of combination of plastic materials (blends) and therefore, to date, non-recyclable. Consequently, these gears end up being incinerated.

Although high-abrasion tolerant fibres such as PA and PET are non-biodegradable, they can considerably reduce the generation of particles caused by wear and tear of dolly ropes and demersal seine ropes caused by abrasion due to contact with the seabed. Føre et al. (2023) showed that PA and PET were 3–5 times more abrasion resistant than standard PE/PP Danline used in demersal seine ropes and PE/PP/PET used in dolly ropes. Moreover, PA and PET are not blended or combined with other materials, thus it is possible that they can be recycled after use.

In recent years, the development of biodegradable polymers has provided new ways of mitigating the environmental impact of the fossil-based non-degradable plastics commonly used in fishing gears. Biodegradation of plastics is understood as the microbial conversion of all its organic constituents to carbon dioxide (CO2) (or carbon dioxide and methane in conditions where oxygen is not present), new microbial biomass and mineral salts, within a timescale short enough not to lead to lasting harm or accumulation in the open environment (EU, 2020). Biodegradable plastics are widely perceived, in Europe and internationally, as more environmentally friendly than conventional plastics, which are fossil-based and non-biodegradable (EC, 2022). The EC (2021) highlights the need to limit the use of biodegradable plastics in the open environment only to specify applications for which reduction, reuse or recycling are not feasible. Furthermore, it emphasises that such plastics should not be considered as a solution for inappropriate waste management or littering. Despite their environmental benefits, their processability is a challenge (Arantzamendi et al., 2023). They have low viscosity, high brittleness, and poor toughness (Liu and Zhang, 2011); low modulus and thermal sensitivity (Hamad et al., 2014); high-water vapour transmission (Bahtiar et al., 2018); and oxygen permeability (Poulose et al., 2021). Further, biodegradable plastics are challenging to process compared to conventional plastics due to their hydrophilic nature, thermal instability, low melt strength, and narrow processing window due to the narrow temperature window between melting temperature and degradation temperature (McAdam et al., 2020). Finally, the presence of water in biodegradable plastics leads to unstable processing and degradation. Overcoming these problems will require strategies such as plasticization, blending, chemical/physical modification, addition of nanoparticles or cellulose, and copolymerization (Cruz et al., 2022).

Some commercial biodegradable plastics used in fisheries are poly(butylene succinate-*co*-adipate-*co*-terephthalate) (PBSAT) (Grimaldo et al., 2020), poly(butylene succinate), poly(butylene adipate-*co*-terephthalate) (Park et al., 2007a, 2007b; Kim et al., 2016), polylactic acid, polybutylene succinate co-butylene adipate co-ethylene succinate co-ethylene adipate (Kim et al., 2023). Føre et al. (2023) concluded that the highly abrasion-resistant biopolymers poly(butylene succinate-*co*-

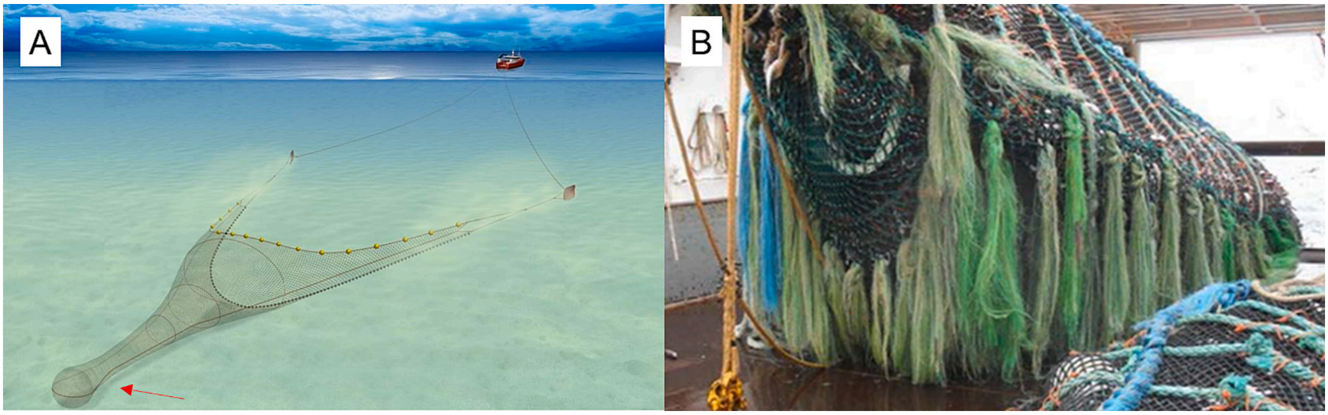

Fig. 1. (A) A demersal bottom trawl (Source: www.seafish.org). (B) Dolly ropes attached to the codend of the demersal bottom trawl (Source: SINTEF Ocean).

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[2] Nofir AS is a Norwegian company that collects and recycles discarded equipment from fishing and fish farming. https://nofir.no/en/.

adipate) (PBSA) and poly(butylene succinate-*co*-terephthalate) (PBST), commercially known as Senbis green rope, could be used in dolly ropes and seine ropes to reduce microplastic production caused by abrasion of these gears due to contact with the seabed.

The goals of this study were to analyse the non-degradable plastic materials currently used in dolly ropes and demersal seine ropes and assess, from a technical and environmental perspective, the potential for replacing them with more abrasion-resistant and biodegradable plastics.

2. Materials and methods

2.1. Plastic materials

Different fibre and rope materials frequently used as dolly ropes and demersal seine ropes in Norwegian demersal fisheries as well as biodegradable alternatives were analysed. Table 1 gives a summary of the materials analysed and Table 2 provides a summary of the tests applied to the various plastic materials assessed in this study.

2.2. Lab tests

Controlled weathering experiment were carried out on three rope materials (PE/PP Standard Danline rope, PP/PE grey dolly rope, and Senbis green rope). These materials were aged under simulated outdoor weathering conditions using a weather-o-meter ATLAS Xenotest 440 (ATLAS Material Testing Technology GmbH, Germany). For these fibre types, 36 pieces of approximately 35 cm length were cut for the tests, yielding 108 samples in total. One set of six pieces of each material was kept aside for reference. An additional set of six pieces of each material was removed from the weathering instrument after approximately 600 h, and another set was removed after 1000 h of ageing. The weathering experiments were performed according to ISO 4892-2 (ISO, 2013) as described elsewhere (Grimaldo et al., 2020).

Optical microscopy was performed using a digital microscope (DSX100 by Olympus Corporation, Tokyo, Japan) to document colour and morphological changes of the different fibres after the weathering test.

Scanning electron microscopy (SEM) was carried out for morphological analysis of the fibre surfaces. SAM was performed using a FEI Nova nano SEM 650 scanning electron microscope (Field Electron and Ion Company, Hillsboro, OR, USA) operated at 5 keV for electron imaging and using a secondary electron detector. The fibre surfaces were coated with a thin layer of evaporated gold to make them conductive.

Attenuated total reflection-Fourier transform infrared spectroscopy (ATR-FTIR) was used to investigate chemical changes of the materials caused by weathering. All measurements were carried out using an Agilent Cary 670 spectrometer (Agilent Technologies, Santa Clara, CA, USA) equipped with a diamond ATR crystal. ATR-FTIR spectroscopy was also employed to estimate the PE content present in PP, as described elsewhere (Larsen et al., 2021). A calibration curve was prepared based on analyses of PP/PE blends with known compositions. To determine the PE content in PP samples with unknown PE content, the following equation was utilized:

$$\%\mathrm{PE} = 120.9\mathrm{r}^2 - 21.97\mathrm{r} + 100,$$

where the ratio (r) was calculated following Camacho and Karlsson (2004):

$$r = 1168\ \mathrm{cm}^{-1} / \left(1168\ \mathrm{cm}^{-1} + 716\ \mathrm{cm}^{-1}\right)$$

Differential scanning calorimetry (DSC) measurements were made using a TA Instruments DSC 2500 (New Castle, DE 19720, USA). During analysis, the samples were first cooled from room temperature down to −70 °C at a rate of 10 °C/min, then heated at a rate of 10 °C/min from −70 °C up to 250 °C, and then subjected to an isothermal step for 3 min at 250 °C. Thereafter, the samples were cooled to −70 °C at a rate of 10 °C/min followed by a second heating to 250 °C at a rate of 10 °C/min. For Senbis green rope, the maximum temperature used was 200 °C. The curve from the second heating was used to determine the crystalline melting points (T_M) and the crystalline melting enthalpies (ΔH_M). Sample weights ranged from 4.1 to 8.3 mg.

X-ray Photoelectron Spectroscopy (XPS) was used to investigate the chemical composition, particularly the oxygen content, at the surface of the three different rope materials before and after weathering. X-ray photoelectron spectra were recorded using a Theta Probe ARXPS system (Thermo Fisher Scientific, Waltham, MA, USA) with monochromatic Al Kα radiation and a spot size of 200 μm. In addition, low-energy electron flooding was used to compensate for surface charging. The pass energy was set to 160 eV for the survey spectra and 40 eV for the high-resolution spectra of the core levels, which were C 1s and O 1s. Spectral processing was performed using Casa XPS computer software. The C-C component of the C 1s peak was used to calibrate the binding energy axis.

Tensile testing was carried out to measure the mean tensile strength and elongation at break of the Senbis green rope samples after 0 h, 595 h, and 1000 h of controlled weathering. Tensile strength, defined as the stress needed to break the sample, is given in MPa. Strain at break, defined as the length of the sample after it had stretched to the point when it breaks, is given as a percentage relative to the initial size. The tensile tests were performed with a universal testing machine (Z250 by ZwickRoell GmbH, Ulm, Germany) using a 2.5 kN load cell, a test speed of 50 mm/min with a grip-to-grip distance of 100 mm according to an in-house developed procedure. Three replicates were analysed from each set of specimens of the unaged and aged materials. The specimens were

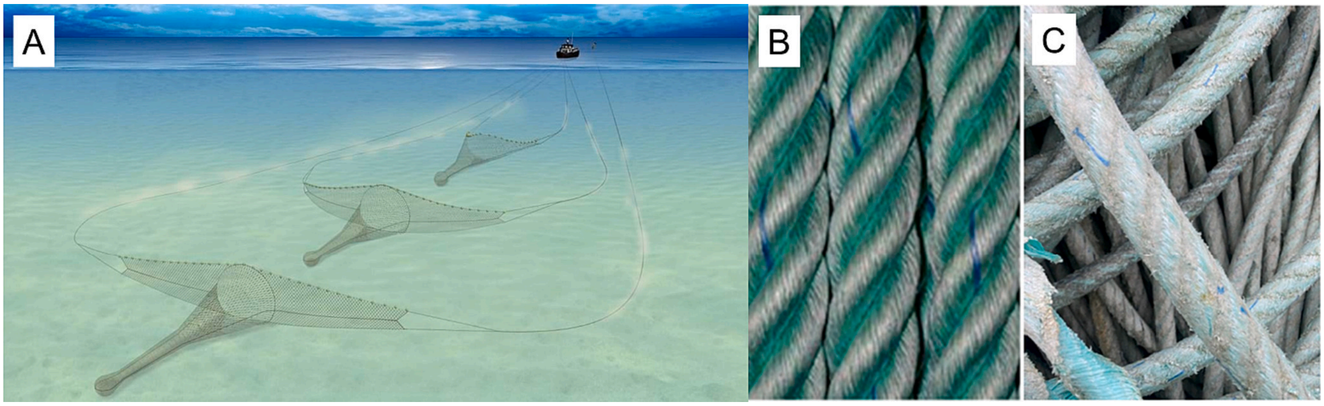

Fig. 2. (A) The working principle of demersal seining. The net is towed by long (up to 4000 m) combination ropes (36–60 mm in diameter) that are dragged over the seabed to create visual effects, sand clouds, and noise to herd the fish into the net (Source: www.seafish.org). (B) 50 mm demersal seine ropes when they are new, and (C) the same ropes after being used for one season (Source: SINTEF Ocean).

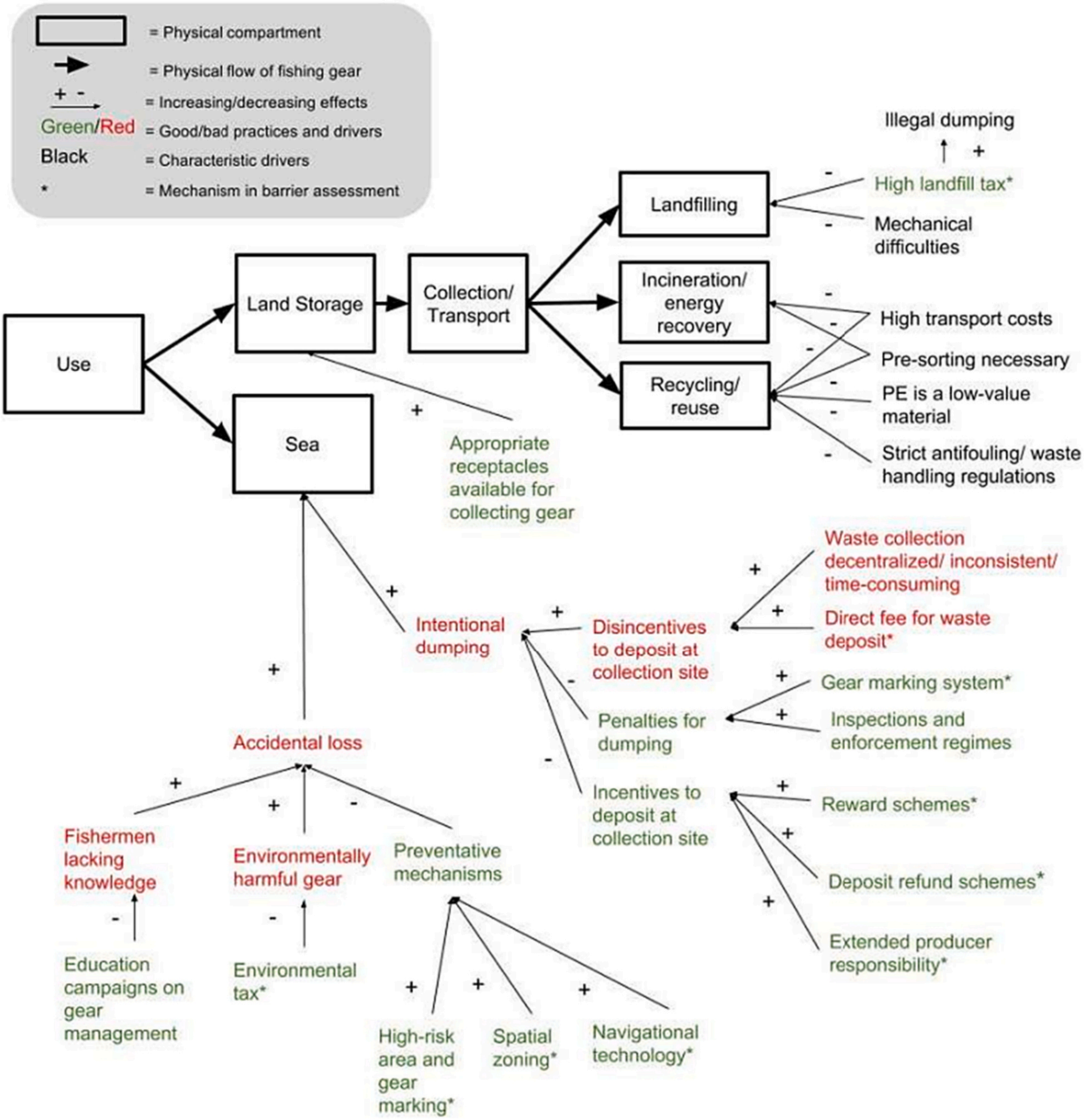

Fig. 3. Flowchart showing the positive (+) and negative (−) drivers that are associated with fishing gear collection and EOL treatment possibilities (reproduced from Brodbeck, 2016).

conditioned at 23 °C and 50 % RH for at least 48 h prior to testing. The testing was performed at room temperature. The tensile modulus was determined from the initial, linear part of the stress-strain curve, between 0.025 % and 2 % strain.

2.3. Field tests - wear and tear of the materials under service life conditions

Bottom trawl experiments were designed to assess the wear and tear tolerance of dolly ropes under standard commercial fishing conditions. The experiment was conducted on board the bottom trawler “MTR Hermes” (55 m LOA) in November 2022 and January–March 2023 off the coast of Northern Norway and in the Barents Sea. MTR Hermes operated two identical bottom trawls simultaneously, allowing for the parallel testing of two codends. For this experiment, we utilized two specially designed codends. Codend 1 consisted of dolly ropes made of standard PP/PE/PET fibres (control) and Senbis green ropes (test). Codend 2 consisted of dolly ropes made of standard PP/PE/PET fibres (control) and PE/PET dolly ropes (test). The different dolly rope materials were arranged in a way that allowed them to be towed simultaneously, subjecting them to similar abrasion conditions (Fig. 4). The experiment lasted for 37 days and included more than 110 tows and approximately 330 h exposure of the dolly ropes to the seabed.

Demersal seine experiments were designed to assess the wear and tear tolerance of different rope materials under standard commercial fishing conditions. The experiment was conducted on board the demersal seiner “MS Fortuna” (30 m LOA) in November–December 2022 off the coast of Northern Norway. PE/PP Standard Danline ropes served as the control material, and biodegradable PBSA, PE/PET, and PA ropes were the test materials. Each rope, measuring 20 m in length, was attached to the 60

Table 1
Summary of materials analysed.

Materials	Description	Application
PP/PE/PET dolly rope[a]	Fossil-based and on-degradable 12 mm thick rope made of a mix of PP/PE/PET fibres that are twisted together and frequently attached to trawl codends as dolly ropes. These served as reference material for dolly ropes	Dolly rope
PP/PE grey dolly rope	Fossil-based and non-degradable 12 mm thick rope made of a mix of PP/PE/PET fibres that are twisted together and frequently attached to trawl codends as dolly ropes. We randomly chose one grey 1.5 mm PE/PP fibres for our analysis in the laboratory.	Dolly rope
Senbis green rope[b]	Biodegradable polyester commercially known as "Senbis green rope". This material is specially designed as dolly rope. Senbis green rope consists of 50 monofilaments, each 1.4 mm thick. We used this 1.4 mm fibres in our analysis	Dolly rope
PE/PP Standard Danline rope[c]	Fossil-based and non-degradable PE/PP blend 3-strand 12 mm thick rope, known as Danline, which is frequently used as a plastic coating for demersal seine ropes and for dolly ropes. This served as the reference material for demersal seine rope.	Dolly rope and demersal seine rope
PBSA rope[d]	Biodegradable 3-strand twisted 12 mm PBSA ropes	Demersal seine rope
PA rope	Fossil-based and non-degradable 3-strand twisted 12 mm thick PA rope	Demersal seine rope
PE/PET autoline rope[e]	Fossil-based and non-degradable 3-strand twisted 11 mm thick PE/PET autoline rope. It is commonly used as main line by the industrial longline fleet, but because of its abrasion resistance it was used as dolly rope in this study.	Demersal seine rope

[a] Supplied by Vonin AS. https://www.vonin.com/.

[b] Supplied by Senbis Polymer AS. Its commercial name is green dolly rope. https://www.senbis.com/products/marine-degradable-fishing-net-protection-dolly-rope/.

[c] Supplied by Selstad AS. Its commercial name is Danline. https://selstad.no/en/products/selstad-rope/.

[d] Supplied by LG Chem, South Korea. https://www.lgchem.com/sustainability/eco-product_letzero.

[e] Supplied by Mustad Autoline AS. https://mustadautoline.com/.

mm ground rope of the seine, with two replicates per material type, and they were deployed on two distinct types of seine nets. The ropes were arranged in a way that allowed all rope materials to be towed simultaneously, exposing them to similar abrasion conditions (Fig. 5). The experiment lasted for 26 days and included close to 50 tows and approximately 400 h exposure of the ropes to the seabed.

Prior to and immediately following the experiments, we conducted measurements and weight assessments of 24 samples of each of the materials used for the dolly rope experiment and all the rope samples used in the demersal seining test. This allowed us to assess the relative material loss caused by wear and tear throughout the experimental period.

2.4. *Sediment absorption assessment*

It is crucial to consider the weight increase caused by sediment absorption during the field experiment to accurately estimate the weight reduction, as the different materials exhibit differing abilities to absorb sediment. To address this, we employed a method described by Imhof et al. (2012) for particle density separation using zinc chloride. The zinc chloride acts as a separation liquid which, due to its corrosive properties, facilitates the detachment of plastic particles from sediment particles and/or organic material. To determine the sediment uptake for each material, two samples from each material used in the demersal seine experiment were taken. These samples underwent rigorous beating and shaking, causing the release of debris. Subsequently, the separated debris was subjected to particle separation.

2.5. *Assessment of the materials' recycling suitability*

Since PA, PE, and PP are single plastic materials that can be recycled, the samples of PE/PP Standard Danline and PA ropes used in the demersal seine experiment were not assessed for recycling suitability. Therefore, the plastic materials consisting of other combinations of plastics (i.e., PP/PE/PET dolly rope, PE/PET dolly rope, and the biodegradable Senbis green rope) were sent to Nofir AS's recycling facility in Lithuania. The recycling suitability of the used materials was assessed, and the material content and its properties were investigated. At Nofir AS, the incoming materials are sorted and processed in line with the recycler's specifications before being sent off as raw material for material recycling. Nofir AS's own laboratory is linked to the production facility, where various tests, such as moisture content and degree of contamination in the materials, are carried out to ensure that the materials handled are of high quality.

3. Results

Optical microscopy and SEM showed that the studied ropes (PP/PE grey dolly rope, PP/PE Standard Danline rope, and Senbis green rope) did not show any significant colour change after controlled weathering, as evidenced by optical microscopy (Supplementary material 1). Further, there were no significant changes in surface structure or other morphological changes, such as cracks or fragmentation, observed after ageing, as shown by SEM (Supplementary material 2).

The ATR-FTIR analysis of the PP/PE grey dolly rope and PE/PP Standard Danline rope samples revealed variations in the PP/PE ratio. The estimated percent PE in the analysed samples was 47 ± 9 % (based

Table 2
Summary of tests and analyses of the samples. Scanning electron microscopy (SEM), Attenuated total reflection-Fourier transform infrared spectroscopy (ATR-FTIR), Differential scanning calorimetry (DSC), X-ray Photoelectron Spectroscopy (XPS).

Sample description	Lab tests				Field tests	
	Controlled weathering	Optical microscopy, SEM, ATR-FTIR, DSC, XPS	Tensile testing	Sediment absorption	Wear tests of bottom trawl nets	Wear tests of demersal seine nets
PP/PE/PET dolly rope	X	X			X	
PE/PP Standard Danline rope	X	X		X	X	X
Senbis green rope	X	X	X ([a])		X	
PBSA rope				X		X
PA rope				X		X
PE/PET autoline rope				X	X	X

[a] Senbis green rope was the only material subjected to tensile testing. Tensile test results for the other materials are found in the literature (Grimaldo et al., 2020; Guo et al., 2020).

Fig. 4. A trawl codend showing the arrangement of the test (red) and control materials (blue) (left panel). For codend 1, the control material was PE/PP/PET dolly ropes, and the test material was Senbis green rope. For codend 2, the control material was PE/PP/PET dolly ropes, and the test material was PE/PET ropes. The red and blue circles indicate the areas where samples were taken to be length measured and weighed. The photographs to the right show codend 1 with PE/PP/PET dolly rope (blue, red, green fibres) and the Senbis green rope dolly rope (white fibres) before the start of the fishing trials. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

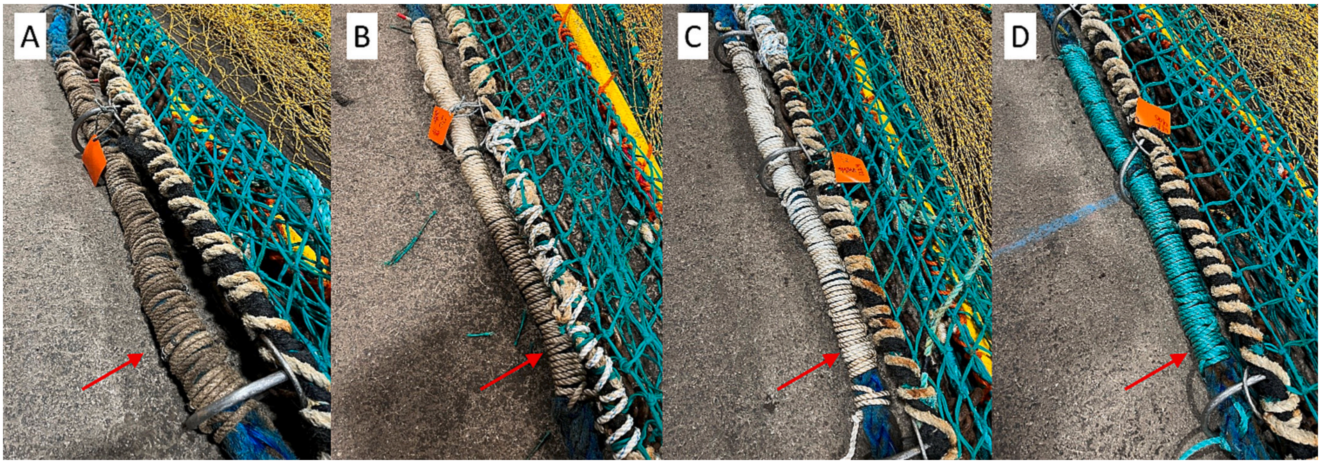

Fig. 5. Rope samples that were attached (wrapped) to the demersal seine's ground rope to expose them to abrasion from contact with the seabed. A) PA rope, B) PE/PET rope, C) Biodegradable PBSA rope, and D) PE/PP Standard Danline rope (Source: SINTEF Ocean).

on 4 replicates) for the PP/PE grey dolly rope and 37 ± 15 % (based on 6 replicates) for the PP/PE Standard Danline rope. For both the PP/PE dolly rope (Fig. 6A) and PE/PP Standard Danline rope (Fig. 6B) samples, an additional broad absorption peak between 1700 and 1800 cm^{-1} was observed after 595 h of weathering, and it increased further after 1000 h. This was most likely due to oxidation, as this wave number range corresponds well with the absorption band of a carbonyl group (La Mantia et al., 2023). No other significant changes were observed in the FTIR spectra of these materials during ageing, suggesting little chemical degradation of these materials. FTIR analysis of the Senbis green rope revealed that it was made of a polyester-like PBST. This result is supported by the presence of absorption peaks at 1712, 1268, and 728 cm^{-1}, which are consistent with this material (Yang et al., 2018). However, it is difficult to determine the exact composition of this material from a FTIR spectrum. After 595 h and 1000 h of weathering, the Senbis green rope showed a decrease of the absorption peaks at 1268 and 728 cm^{-1}, suggesting degradation of the material (Fig. 6C). A previous study of controlled weathering of monofilaments of poly (butylene succinate *co*-adipate-co-terephthalate) (PBSAT), which is very similar to poly(butylene succinate-*co*-terephthalate) (PBST), showed the same trend for these absorption peaks (Grimaldo et al., 2020).

DSC results are summarized in Table 3. For both PP/PE grey dolly rope and PE/PP Standard Danline rope, the crystalline melting points of 132 °C (high-density PE) and 163 °C (PP) were observed for unexposed material as well as for samples weathered for 595 h. However, after 1000 h of weathering, a new crystalline melting point at 145/148 °C was observed for both materials in addition to the two other crystalline melting points. This indicates that incomplete crystalline structures of PP with lower crystalline melting points had formed. This phenomenon might be due to thermal degradation resulting in lower molecular weight PP molecules that can form fewer perfect crystals (Saikrishnan et al., 2020).

After 595 h of weathering, the crystalline melting peak of Senbis green rope at 76 °C completely disappeared. After 1000 h of exposure, a

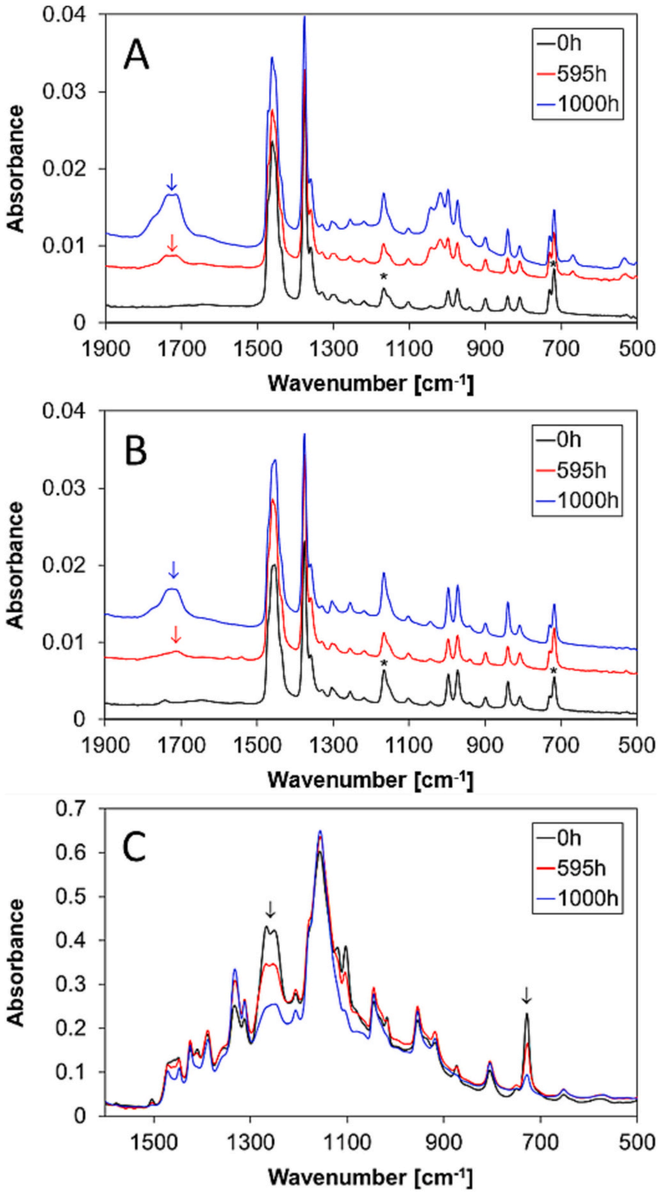

Fig. 6. FTIR spectra of the PP/PE grey dolly rope (A), PE/PP Standard Danline rope (B) and Senbis green rope (C) after 0, 595, and 1000 h of weathering. ↓ denotes the absorption bands that changed due to exposure, and * denotes the bands used for estimating the PE/PP ratio. The absorbance values were offset along the y-axis for clarity. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

small cold crystallization peak appeared at 69 °C ($T_{CC}/\Delta H_{CC}$) that was not present in the reference sample or the 595 h sample. It is difficult to interpret the DSC results for this material because little is known about its detailed chemical composition. To assess the reproducibility of the DSC measurements for the Senbis green rope, three replicates of the material after 595 and 1000 h of exposure were tested. As depicted in Fig. 7, the reproducibility of the measurements was good.

XPS was used to investigate the chemical composition, and in particular the oxygen content, at the surface of the three different rope materials (PP/PE grey dolly rope, PP/PE Standard Danline rope, and Senbis green rope) before and after weathering. Table 4 summarises the oxygen-to-carbon ratios. Compared to the unexposed samples, the XPS results show a clear increase of the oxygen content in the rope materials after weathering, which indicates that the surfaces were oxidised, and this correlates well with the results from the FTIR investigations. Senbis green rope is made of a polyester and thus already contains a considerable amount of oxygen before weathering compared to the PP and PE rope materials.

Table 3

DSC results for the second heating of the three rope materials before and after weathering.

Sample	T_{CC} [°C]	ΔH_{CC} [J/g]	T_M [°C]	ΔH_M [J/g]
Senbis green rope 0 h	–	–	76.3/85.5 123.9	26.7[a] 4.5
Senbis green rope 595 h	–	–	86.7 120.6	22.3 4.3
Senbis green rope 1000 h	68.5	0.40	88.9 124.7	22.1 4.7
PP/PE Standard Danline 0 h	–	–	132.7/163.6	122.7[a]
PP/PE Standard Danline 595 h	–	–	132.3/161.7	126.7[a]
PP/PE Standard Danline 1000 h	–	–	131.6/148.7/160.5	132.8[a]
PP/PE grey dolly rope 0 h	–	–	132.1/162.6	125.3[a]
PP/PE grey dolly rope 595 h	–	–	132.5/162.9	113.8[a]
PP/PE grey dolly rope 1000 h	–	–	131.1/145.3/159.2	128.0[a]

[a] For all peaks when overlapping.

Tensile testing showed that with increased weathering, the Senbis green rope became stiffer and more brittle, as indicated by increased tensile modulus, reduced tensile strength, and reduced strain at break (Fig. 8). The same behaviour was observed in a previous study (Grimaldo et al., 2020) of controlled weathering of monofilaments of PBSAT, which is a material very similar to Senbis green rope.

During the 37-day bottom trawl experiment, codend 1 lost 3.8 % of the PE/PP/PET dolly ropes due to abrasion with the seabed, and codend 2 experienced a weight reduction of 0.7 %. In contrast, the Senbis green rope material exhibited a substantial weight loss of 18.4 % of the original weight during the same period (Table 4). The unexpected large loss of Senbis green rope material from the codend was mainly caused by the lack of a reliable attachment technique rather than by material wear and tear. The stiff and smooth nature of the Senbis green rope material prevents it from being knotted in a manner similar to that of PE/PET and PP/PE/PET dolly ropes. Therefore, a specialized method for securely attaching Senbis green rope material to the codend needs to be developed and perfected. Conversely, the PE/PET dolly ropes performed very well and displayed no loss of weight due to abrasion (Table 5). In fact, the material experienced a slight weight increase (0.9 %) after the experiment, possibly due to sediment absorption, incomplete drying, or a combination of these factors.

During the 26-day demersal seine experiment, the PE/PET rope was the most abrasion-resistant material. When exposed to normal commercial fishing conditions, the PP/PET ropes lost 1.1 % of their weight due to abrasion with the seabed. This represents a 52.2 % reduction in weight loss compared to the standard (control) PE/PET Danline material, which lost 2.3 % of its weight during the same time. PA and PBSA lost 2.0 % and 2.2 % of the original weight, respectively (Table 6).

Nofir AS's material recyclability assessment was limited to the analysis of material composition, specification of identified polymers in the samples, and an estimation of the quantity and proportion of the various polymers. It did not include the quality and degree of purity of identified polymers compared to suitability for recycling and need for processing. The analysis confirmed that none of the samples analysed could be recycled, mainly because they were mixtures of different polymers (PE/PP and PE/PP/PET) or because there are no established methods available (Senbis green rope).

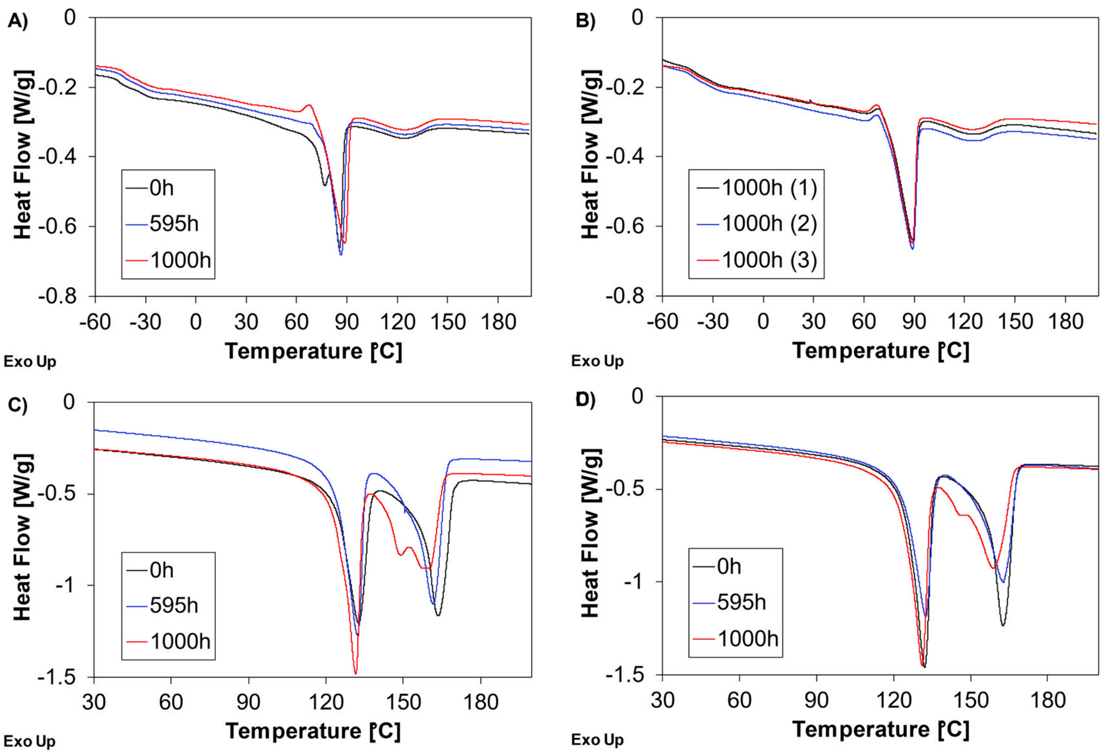

Fig. 7. DSC results for the second heating of the unexposed and weathered materials: A) Senbis green rope, B) Repeatability for Senbis green rope, C) PE/PP Standard Danline rope, and D) PP/PE grey dolly rope. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 4
Oxygen-to-carbon ratios of the rope materials before and after weathering.

Sample	0 h	1000 h
PP/PE grey dolly rope	0	0.02
PE/PP Standard Danline rope	0.01	0.03
Senbis green rope	0.30	0.36

4. Discussion

Analysis after accelerated ageing revealed that both tested PP/PE materials (PP/PE grey dolly rope and PE/PP Standard Danline rope) as well as the biodegradable polyester material (Senbis green rope) showed signs of degradation after 1000 h of exposure. Even though no significant changes in the surface topography (SEM) or colour changes (optical microscopy) could be detected, chemical analyses (FT-IR and XPS) revealed increased oxidation of the materials during the ageing experiment. DSC analysis of the PP/PE materials showed changes in crystallinity during ageing, which indicates a decrease in molecular weight. The tensile test of the Senbis material showed that the material became stiffer and more brittle during ageing. The degradation mechanism for the Senbis material could be a combination of oxidation and hydrolysis resulting in decreased molecular weight.

The observed loss of material from the PE/PP/PET dolly rope during the field tests is in line with reported quantities of fossil-based non-degradable plastics left at sea during the service life of this gear component (Martinussen, 2021). The sea trials revealed a material loss of 0.7–3.8 % over a 37-day period, which upscaled to the entire dolly rope is equivalent to the production of up to 2.8 kg of MPs. It should be noted that the wear and tear of dolly ropes can vary depending on factors such as the type of sediment present on the seabed (i.e., clay, sand, gravel, rocks) and the fishing areas where the trawl fleet operates. Thus, it is expected that the results of this experiments would differ if conducted at a different time, location of if conducted for a longer period than 37 days. Syversen et al. (2022) estimated the mass loss of standard PE/PP/PET dolly ropes to be between 30 % and 70 % over a period no longer than 6 months.

Similarly, the loss of material estimated in the demersal seine experiments (2.0–2.3 %) reflects the quantities of plastic particles originated by this gear during its service life. A 2.0–2.3 % loss of our 40 m PE/PP rope sample is equivalent to 1.9–3.4 kg of MPs originated by one vessel during 50 tows in the 26-day experiment. Linearly extrapolated to one fishing season, where a vessel like the one used in our field test normally uses 3300 m, 50 mm thick PE/PP rope per arm, and carried out around 600 tows, the loss would be equivalent to approximately 2930–3370 kg of MPs. This quantity represents a 24–28 % weight reduction of the demersal seine ropes during its service life. This estimate is larger than earlier estimates based on measurements of new and used (disposed) demersal seine ropes (Syversen et al. (2022) estimated that approximately 14 % of the rope is worn off in 1 year). However, the difference between our estimates and that from Syversen et al. (2022) may be partially explained by our assumption of linear extrapolation.

Senbis green rope is a biodegradable material specifically developed for dolly rope applications. Despite its high abrasion tolerance, field testing revealed a significantly large loss of material (18.4 %) over the course of a 37-day experiment. This percentage was significantly higher than that expected based on controlled lab abrasion experiments conducted with the same material (Føre et al., 2023). The discrepancy between the loss of material in the field experiments and the abrasion resistance measured in lab abrasion tests can be attributed to the smooth and slippery characteristics of the material, which prevents it from being knotted and necessitates the use of plastic cable ties for fixation. However, the cable ties easily slid off, resulting in loss of material from the trawl codend. Hence, for future field tests it is crucial to find a better method for securely fastening the Senbis green rope to the trawl codend.

Generally, biodegradable polyester materials such as the Senbis green rope and PBSA tested in this study could offer a more environmentally friendly alternative to fossil-based non-biodegradable standard

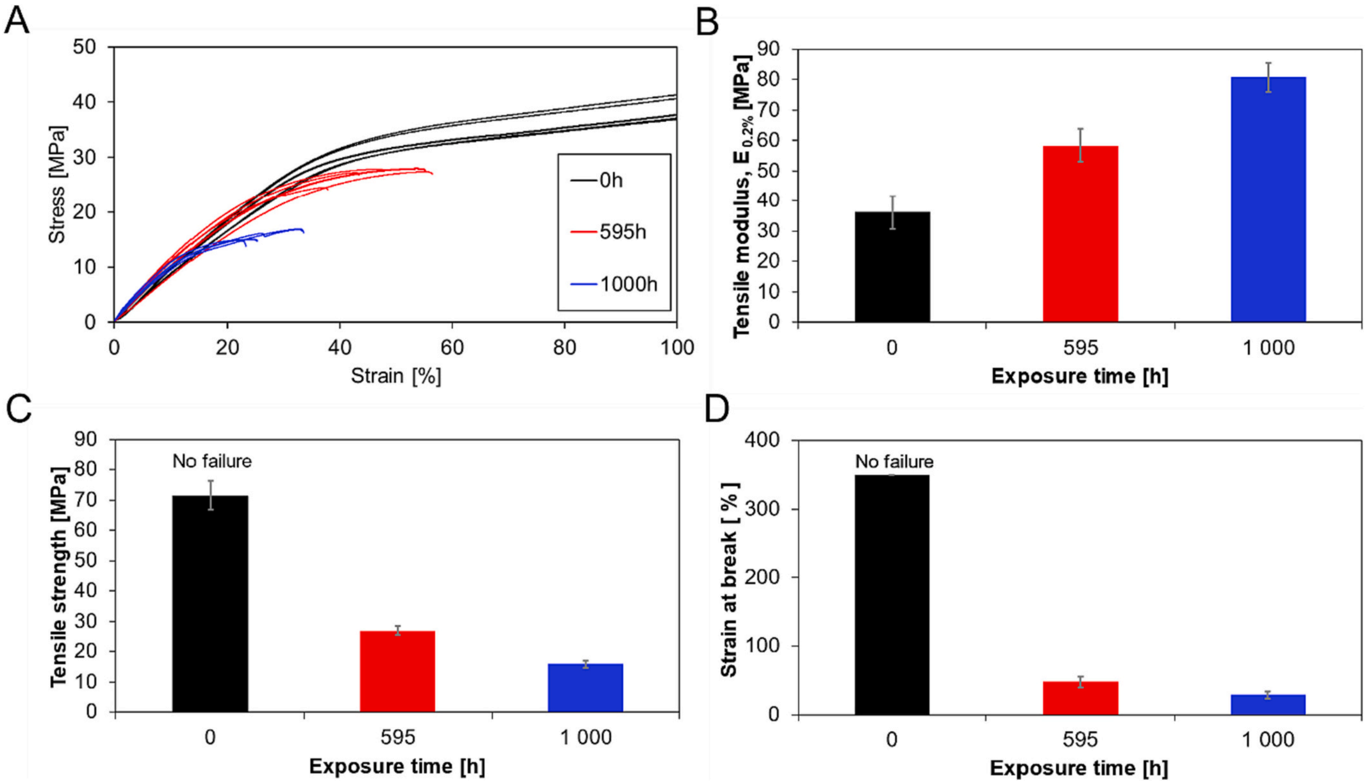

Fig. 8. Tensile results for the weather-O-meter tests of aged Senbis green rope. A) Stress-strain curve. Note that the graph has been truncated at 100 % because the 0 h specimens could not be tested to failure but rather to 350 %. B) Tensile modulus, C) Tensile strength, and D) Strain at break. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 5

Scaled-up weight (kg) reduction (%) of dolly ropes measured before and after the 37-day sea trial. The weight of sediment absorbed by the ropes during field testing was subtracted from the weight of the plastic material.

Codend 1	Before	After	Reduction
PP/PE/PET dolly rope	33.0	31.7	−3.8 %
Senbis green rope	92.2	77.9	−18.4 %

Codend 2	Before	After	Reduction
PP/PE/PET dolly rope	30.3	30.1	−0.7 %
PE/PET dolly rope	72.3	73.0	0.9 %

Table 6

Scaled-up weight (kg) reduction (%) of the ground rope measured before and after the 26-day field trial. The weight of sediment absorbed by the ropes during field testing was subtracted from the weight of the plastics material.

Rope material	Before	After	Reduction
PA	171.0	168.0	−2.0 %
PE/PP Standard Danline	140.6	137.0	−2.3 %
PE/PET dolly rope	176.9	175.1	−1.1 %
PBSA rope	148.5	145.0	−2.2 %

materials, as they degrade faster in the environment (Luo et al., 2010; Way et al., 2018; Nakayama et al., 2019) and thus can reduce the impact of MPs caused by wear and tear of fishing gears during their service life. However, at the end of their service life these materials would most likely be incinerated or landfilled because currently there are no viable recycling methods for biodegradable polymers and composting facilities that could receive these materials are scarce. This scenario is not favourable from a circular economy perspective. From an environmental perspective, however, the use of biodegradable polyesters such as PBST or PBSA in the construction of demersal seine ropes could still be a better alternative to the standard materials used in demersal seine ropes (PE, PP, and steel core) because the current waste management of discarded demersal seine ropes is mainly landfilling, energy recovery, or being dumped at sea. Hence, the use of biodegradable polyesters would reduce the environmental impact of MPs caused by wear and tear.

Nofir AS's recyclability analysis confirmed that none of the samples analysed could be recycled, mainly because they were mixtures of different polymers (PE/PP and PE/PP/PET) or because there are no established methods for biodegradable polyesters (Senbis green rope and PBSA). Technically, it is possible to separate most plastics into recognizable streams, but not all plastic streams are mechanically processable due to various chemical and mechanical behaviours and thermal properties; only thermoplastic polymers (e.g., PE, PP, and PET) are mechanically recyclable (Thiounn and Smith, 2020). Recycled polyolefin resins from fishing nets (PE and PP are among the most common ones) seem to have poor properties due to the presence of contamination. Juan et al. (2021) showed how blends of used PE fishing nets with different types of virgin resins have some potential for usage in packaging. For demersal trawling, a dolly rope attached to a codend of the same material would be preferable for recycling purposes. This is not the case in the fishery today, as different dolly rope materials are attached to either PA or PE codends. Recycled PE and PP have a significantly lower economic value (88 % and 73 %, respectively) than recycled PA, with average values of €0.6, €1.3, and €4.7. Recycling fishing gear that is made up of different materials can often be financed by the valuable fractions in the fishing gear, such as PA and lead (Heidi Ruud, Nofir AS, pers. comm).

An alternative to mechanical recycling is chemical recycling, which produces chemical feedstock that can replace fossil-based feedstock (EU, 2020). Emerging chemical and biological methods can enable the upcycling of increasing volumes of heterogeneous plastic and biodegradable plastic waste into higher quality materials. Furthermore, clear regulation and financial incentives remain essential to scale up from niche polymers to large-scale biodegradable plastic market applications with a truly sustainable impact. Using PA as an alternative material for demersal seine ropes and dolly ropes opens the possibility of using recycled PA in the same fishing gears and significantly limiting the level of emissions. In addition, emphasis should be placed on the wear resistance and extended service life that can compensate for a higher price difference with respect to traditional PE/PP or mixed PE/PP/PET. Extended service life of the gears will play a significant role in the overall emissions picture (EC, 2020).

Nofir AS's material recyclability analysis was limited to the analysis of material composition, specification of identified polymers in the samples, and an estimation of the quantity and proportion of the various polymers. It did not include the quality and degree of purity of identified polymers compared to suitability for recycling and need for processing. The analysis also did not include the degree of wear and breaking strength compared to suitability for inclusion in a recycling process, the melting index for each of the different materials, the degree and type of contamination (e.g., pollution absorbed from the marine environment in the form of heavy metals/toxins, sand), or an overview of additives in the materials (e.g., plastic softeners, flame retardants). It is important to consider that the additional use of compatibilizers and fillers in combination with other additives may have an impact on the environment, as there are several common polymer additives available to improve the chemical and physical properties of the material (Madina and Endres, 2021; Kumar et al., 2023). Fillers themselves can be different from the matrix of the base polymer and may require costly separation before the polymer can be recycled. However, extensive research into fillers has led to rapid and cost-effective upgrades to mechanically recycled polymers, which allow polymers that were destined for landfill to be repurposed for secondary applications in which impact resistance takes precedence over flexibility (Madina and Endres, 2021).

5. Conclusion

The results presented in this study demonstrate that combinations of PE/PP/PET polymer fibres currently used in bottom trawls and demersal seines have a negative environmental impact. They do not apply the most desirable circular solution to end of life, as they lead to significant production of MPs at sea and exhibit limited recyclability. Hence, these combinations of materials should be avoided. One potential solution, although more expensive, would be to replace fibres made of PE/PE/PET polymers with single-polymer materials such as PA and PET, which are more resistant to abrasion. From a circular perspective, the utilization of highly abrasion-resistant materials like PA and PET (Føre et al., 2023) is a promising solution, and the suitability of these materials for recycling contributes to a more sustainable approach. Despite being fossil-based non-degradable, these materials can potentially reduce the amount of MPs during their service life.

As trawl codends are typically made of PA or PE/PP netting, it is advisable to use the same type of materials for dolly ropes. This would eliminate the time-consuming disassembly of dolly ropes from codend netting prior to recycling and thus reduce costs. Using PA as an alternative material for demersal seine ropes and dolly ropes also opens the possibility of using recycled PA in the production of new fishing gears. The high wear resistance would extend the service life, which might compensate for the higher price compared to standard materials, and it could potentially reduce the amount of MPs produced.

The use of biodegradable polymers is another solution that could potentially reduce MPs pollution generated from demersal trawling and seining. Biodegradable materials such as Senbis green rope and PBSA are more environmentally friendly than non-biodegradable standard materials, as they degrade faster in the environment and thereby reduce the impact of MPs caused by wear and tear of fishing gears during their service life. The benefit would be even higher if the biodegradable materials were highly abrasion resistant. Currently, the lack of available recycling methods and industrial composting facilities means that seine ropes and dolly ropes will most likely end up being incinerated for energy recovery or deposited in a landfill. However, the use of biodegradable polymers in the construction of demersal seine ropes and dolly ropes could still be a better alternative to standard materials. We conclude that there is a need to develop a recovery technique that enables recycling of biodegradable polyesters.

CRediT authorship contribution statement

Eduardo Grimaldo: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Visualization, Writing – original draft. **Christian W. Karl:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Writing – original draft. **Anja Alvestad:** Data curation, Investigation, Formal analysis, Writing – original draft. **Anna-Maria Persson:** Data curation, Investigation, Formal analysis, Writing – original draft. **Stephan Kubowicz:** Data curation, Investigation, Formal analysis, Writing – original draft. **Kjell Olafsen:** Data curation, Investigation, Formal analysis, Writing – original draft. **Hanne Hjelle Hatlebrekke:** Data curation, Investigation, Formal analysis, Writing – original draft. **Grethe Lilleng:** Data curation, Investigation, Formal analysis, Writing – original draft. **Ilmar Brinkhof:** Data curation, Investigation, Formal analysis, Writing – original draft.

Declaration of competing interest

The current work in this study does not involve any competing interest of finical disclosures for any of the authors or institutions.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2023.115634.

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