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Can biodegradable materials reduce plastic pollution without decreasing catch efficiency in longline fishery?

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ABSTRACT

Longlining is a widely used fishing method. During longline fishing, some of the snoods connecting the hooks to the mainline are often lost at sea. Since snoods are made of nylon or polyester, lost snoods contribute to marine plastic pollution. Replacing nylon or polyester with a new material made of biodegradable plastics can potentially reduce macro- and microplastic pollution that is caused by lost snoods. In this study, we estimated the risk for snood loss in a longline fishery targeting haddock (*Melanogrammus aeglefinus* (Linnaeus, 1758)) and Atlantic cod (*Gadus morhua* (Linnaeus, 1758)) in Barents Sea. Further, we compared catch efficiency in this fishery for snoods made of biodegradable and nylon materials. No significant differences were found between the two materials. Therefore, catch efficiency does not represent a barrier for using biodegradable materials in snoods.

1. Introduction

Longlining is a widely used fishing method in different fisheries worldwide (Watson et al., 2006; He et al., 2021). All types of longlines consist of three components: a mainline, snoods and hooks (Fig. 1). The snood (also termed gangion) is a short line connecting mainline with the hook at the other end at regular intervals. Each snood is attached at a certain interval along the mainlines either directly with a knot or by using a clip or swivel usually equipped with a spinner (He et al., 2021). Fish are attracted to the longline by bait on the hooks.

In Norway, demersal longlines are widely used to target demersal fish species such as cod (*Gadus morhua* (Linnaeus, 1758)), haddock (*Melanogrammus aeglefinus* (Linnaeus, 1758)) and Greenland halibut (*Reinhardtius hippoglossoides* (Walbaum, 1792)) in coastal/inshore areas. In 2020, line and longline fisheries contributed to 33.8% of haddock, 19.8% of cod and 39.5% of Greenland halibut landings in Norway (Norwegian Directorate of Fisheries, 2021). The coastal fleet uses both, manually and mechanically baited gears and operates between 10.000 and 30.000 hooks per day (Mustad autoline, 2021a). Their operation is based on daytrips and landing of fresh fish (fresh fish on ice/chilled water). The deep-sea longline fleet (called the autoline fleet) operates mechanized baiting systems with up to 60.000 hooks deployed and hauled per day and their capture periods last for weeks (Larsen and Rindahl, 2008; Mustad autoline, 2021b) since processed fish is packed and stored frozen. This fleet targets similar species as the coastal fleet, while such species like tusk (*Brosme brosme* (Ascanius, 1772)), ling (*Molva molva* (Linnaeus, 1758)), redfish (*Sebastes* spp.) and spotted wolffish (*Anarhichas minor* (Olafsen 1772)) are common bycatch species.

The longline fishery mostly uses synthetic materials such as spun polyester or polyamide 6, herein called nylon, monofilament for the main line and monofilament nylon or twisted polyester for snoods. While the Norwegian deep-sea fleets use snoods made from polyesters, the coastal fleets with manually and mechanically baited gears prefer the monofilament nylon snoods. In demersal longline fishery, longlines (or sections of them) are often lost at sea because of being deployed along rough grounds and because of large abrasion of the materials. Similarly, snoods risk being lost at sea because of, for example, being snagged at the seafloor or during the fishing process when the fish break the snood line and escape with the hook and part of snood.

Because snoods are made from petrol-based synthetic plastic material, they will degrade very slowly in seawater in case of being lost. Furthermore, even after long exposures (i.e., decades), the material does

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not degrade completely – instead it is being broken down into smaller plastic particles and increases macro- and microplastic pollution and releases toxic substances into the marine environment (Moore, 2008). This can negatively impact the food web of the marine ecosystem (Lee et al., 2013; Cole and Galloway, 2015; Desforges et al., 2015; Chae and An, 2017; Lusher et al., 2017). Use of biodegradable plastic to replace synthetic plastic materials such as nylon in fishing gear are being tested in other fisheries such as gillnets (Grimaldo et al., 2018a, 2018b, 2019, 2020) by using biodegradable material made of polybutylene succinate *co*-adipate-co-terephthalate (PBSAT) resin. Such biodegradable material has the properties for being fully degraded after specific time in the seawater by naturally occurring microorganisms (Tokiwa et al., 2009).

Experiments with biodegradable PBSAT materials to replace commonly used nylon material, have shown reduced catch efficiency in gillnet fisheries (Grimaldo et al., 2018a, 2018b, 2019, 2020). Biodegradable PBSAT material has a lower tensile strength (Grimaldo et al., 2020) compared to nylon. Therefore, use of biodegradable PBSAT plastic in the snood material could potentially show a reduced catch efficiency because of the loss of snoods during the fishing process as a result of breaking of the material. An increased material thickness (diameter of the snood) may be needed for biodegradable snoods to provide a similar tensile strength to that of the nylon material. However, earlier trials testing increased snood thickness (diameter) in longline fishery targeting hake (*Merluccius merluccius*) have resulted in a reduced catch efficiency (Herrmann et al., 2017). The reasons for this might be related to the visibility of the snoods to the fish (Herrmann et al., 2017). However, the effect of increased snood diameter is not known in other fisheries.

Additionally, the extent of snood loss by using the biodegradable materials should not exceed the loss of snoods made of nylon to be accepted commercially. In case of increased snood loss by changing of the material, more labor would be involved to replace the loss. It would, furthermore, increase the costs by using additional quantity of snood material and hooks and reduce the capture efficiency during fishing. Although some snood loss is common in the fishery (i.e., 5.9% in the Patagonian toothfish fishery (AFMA, 2010)), the extent of such loss per gear deployment has not been scientifically quantified. Further, longlines using the biodegradable material must obtain a similar catch efficiency to that of nylon snoods to be adopted by the industry, and thereby contribute at reducing marine plastic pollution. Initial tests are needed to provide information whether the new material is initially providing a similar catch efficiency to that of nylon before further proceeding with experiments involving repeated deployments for determining the effect of long-term use of the biodegradable snoods on the catch efficiency.

In this study, we estimated the probability of snood loss using nylon and biodegradable PBSAT materials with two different monofilament thicknesses. Further, we tested the effect of using the biodegradable material with a similar and increased snood material thickness on the catch efficiency of haddock and cod targeted in a coastal longline fishery in Northern Norway. Thus, the aims of this study were to address the following research questions:

- What is the risk for snood loss in coastal longline fishery for haddock and cod?
- Is there any difference in risk for snood loss if the snood material is changed from nylon to biodegradable PBSAT plastic material with equal and increased material thickness?
- Is there any difference in catch efficiency of haddock and cod if the snood material is changed from nylon to biodegradable PBSAT plastic material?
- Would the catch efficiency change if an increased material thickness of biodegradable PBSAT snoods is used?

2. Materials and methods

2.1. Sea trials and experimental setup

Sea trials were conducted onboard a commercial coastal longline vessel “Vardøyfisk 2” (12.95 m LOA) during November 2021. The fishing grounds were located in Northeast Norway between 70°00.00–70°07.64 N and 30°19.85–30°43.68 E. The fishing depth varied between 100 and 240 m. The trials consisted of two series of longlines, where each longline was made from 6 mainlines which consisted of 415 snoods and hooks each. The snoods were attached to a three stranded spun polyester mainline with 5.5 mm diameter. The distance between each snood was 1.3 m. Therefore, the total length of each mainline was 540 m. Prior to each fishing trip, all longlines were manually baited using mackerel (*Scomber scombrus* Linnaeus 1758) and stored in tubs. The longlines of each series were deployed and soaked equally long time in the same area.

In each series, the mainlines with biodegradable and nylon snoods were alternated (Fig. 2) as follows:

> *Series 1*: A longline consisting of three mainlines with 415 snoods each made of biodegradable PBSAT material of 1.0 mm diameter alternated with three mainlines with 415 snoods made of nylon with 1.0 mm diameter.
>
> *Series 2*: A longline consisting of three mainlines with 415 snoods each made of biodegradable PBSAT material with an increased diameter (1.1 mm) alternated with three mainlines with 415 snoods made of nylon with 1.0 mm diameter.

During hauling of the longlines, fish were sorted according to type of the snoods (biodegradable or nylon). All haddock and cod were measured for the total length to the closest cm below. Further, after each fishing trip during the rebaiting, the numbers of lost or damaged snoods for each material type were recorded. New snoods were attached if missing or replaced if damaged where necessary so that the number of

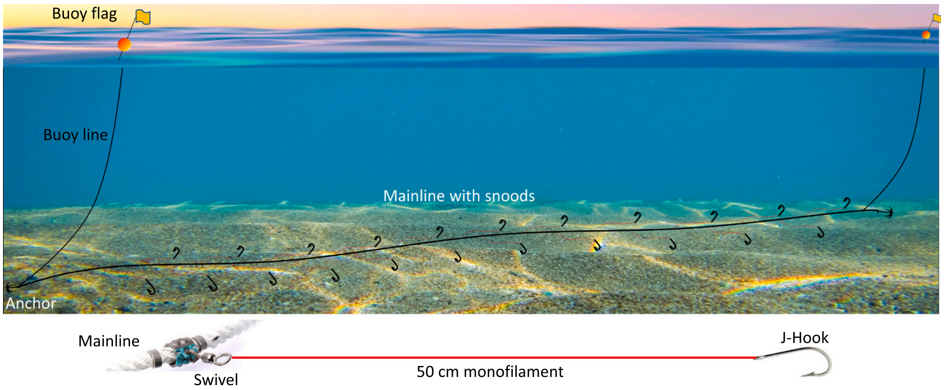

Fig. 1. Illustration of longline components.

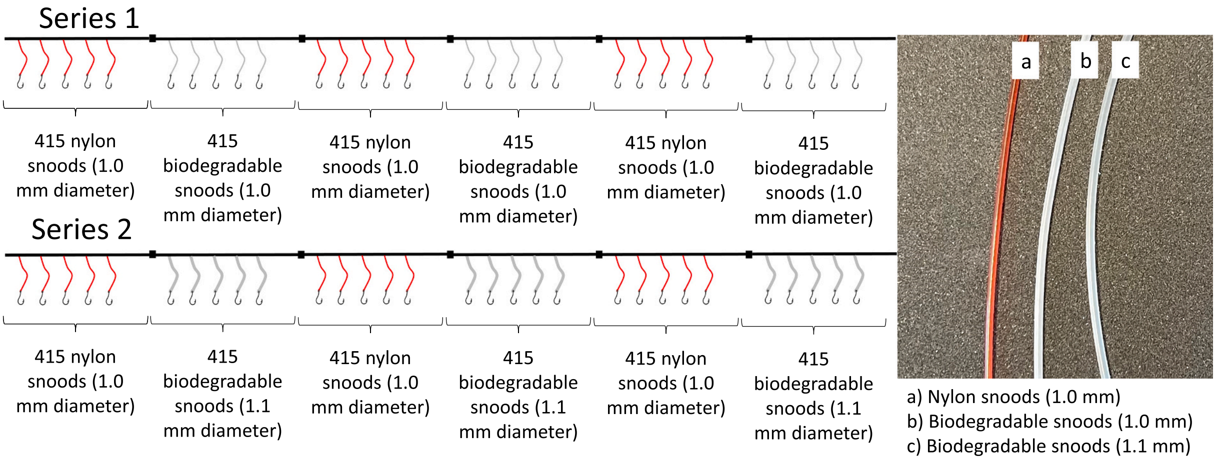

Fig. 2. Experimental setup used during the fishing trials. Series 1 consisted of nylon (a) and biodegradable PBSAT (b) snoods of 1.0 mm diameter. Series 2 consisted of biodegradable PBSAT snoods of 1.1 mm diameter (c) and nylon snoods of 1.0 mm diameter.

snoods was identical for each longline deployment (i.e., 415 snoods per mainline).

2.2. Estimating risk of snood line loss

The risk for losing a snood (P_{loss}) during one deployment of it is quantified by the probability averaged over deployments and snoods of the specific type:

$$P_{loss} = \frac{1}{m}\sum_{i}^{m}\left\{\frac{1}{ns_i}\sum\nolimits_{j=1}^{ns_i} g\left(s_{ij}\right)\right\}$$

$$with \qquad (1)$$

$$g(s) = \begin{cases} 1 \;\forall\; s = lost \\ 0 \;\;\forall\;\; s \neq lost \end{cases}$$

where ns_i is the number of snoods on the mainline in deployment i. s_{ij} is the status (lost or retained) of snood number j after line deployment i. m is the number of deployments.

Estimation of uncertainties for P_{loss} calculated based on Eq. (1) required consideration that the risk may vary between deployments with the same type of snood due to uncontrolled effects in the fishing process. Further, assessing the risk for the individual deployments is subjected to uncertainty (within-deployment variability) because of limited number of snoods being deployed. To account for these uncertainties in the estimations, a double bootstrap method was adapted. This method is well established for evaluating fishing gear selectivity and catch efficiency for fisheries known to be subjected to a similar structure in uncertainties (i.e., Herrmann et al., 2017). The procedure accounts for between-deployment variation in the risk by selecting m deployments with replacement from the pool of deployments of mainlines with the specific snood type (i.e., nylon or biodegradable (1.0 mm or 1.1 mm diameter, respectively)) during each bootstrap repetition. Within-deployment uncertainty in the obtained risk was accounted for by randomly selecting snoods with replacement from the selected mainline. The number of snoods selected from each deployment was the same as the number of snoods used in that deployment (ns_i). The resulting data for each bootstrap were then used to estimate the expected risk for snood loss based on Eq. (1). We performed 1000 bootstrap repetitions and calculated the Efron 95% percentile confidence intervals (Efron, 1982) (CIs) for the estimated probabilities.

To infer the difference ΔP_{loss} between two types of snoods, we used the two populations of bootstrap results obtained by the procedure described above following method described in Larsen et al. (2018) and Herrmann et al. (2018):

$$\Delta P_{loss} = P_{lossB} - P_{lossA} \qquad (2)$$

where P_{lossA} represents the value for P_{loss} for snood type A, and P_{lossB} represents the value for P_{loss} for snood type B. Efron 95% percentile confidence limits for ΔP_{loss} was obtained based on the two bootstrap populations of results (1000 bootstrap repetitions in each) for both P_{lossA} and P_{lossB}. As they were obtained independently, a new bootstrap population of results was created for ΔP_{loss} by:

$$\Delta P_{loss\,i} = P_{lossB\,i} - P_{lossA\,i} \; i \in [1\ldots1000] \qquad (3)$$

where i denotes the bootstrap repetition index. As the bootstrap resampling was random and independent for the two groups of results, it is valid to generate the bootstrap population of results for the difference based on Eq. (3) using the two independently generated bootstrap files (Herrmann et al., 2018). Based on the bootstrap population, Efron 95% percentile CIs were obtained for ΔP_{loss} as described above. In case ΔP_{loss} does not include the value 0.0 in the CIs for P_{loss}, the loss risk between deploying snoods of type A and B, respectively, will be significantly different.

We used an identical approach for estimation of $P_{replacement}$ for need of snood line replacement between longline deployments and difference $\Delta P_{replacement}$ between different types of snoods. We used the statistical software SELNET (Herrmann et al., 2012) to conduct the analysis described above.

2.3. Estimating the length-dependent catch efficiency between longlines with different snood materials

Comparison of catch efficiency between the mainlines with different snood materials in Series 1 and Series 2 was estimated as catch comparison rate and catch ratio (Herrmann et al., 2017). We used the catch information (numbers and lengths of haddock and cod caught with each of the mainlines with different snood materials and diameters) to determine whether there was a significant difference in the catch efficiency averaged over deployments. We used the statistical software SELNET (Herrmann et al., 2012) to analyze the catch data and conduct length-dependent catch comparison and catch ratio analyses. We also tested whether a potential difference between the snood types could be attributed to the size (total length) of haddock and cod. We used the method described in Herrmann et al. (2017) to assess the change in relative length-dependent catch efficiency when changing the snood material in each series. Further, we applied the same method to assess the change in relative length-dependent catch efficiency between snood material types. The method models the length-dependent (l) catch comparison rate ($CC(l)$) and catch ratio ($CR(l)$) summed over all deployments for the full deployment period. We used the double bootstrapping method (1000 bootstrap repetitions) to estimate the 95% CIs for the catch comparison and catch ratio curves following the description in Herrmann et al. (2017). When the catch efficiency of the two types of snoods is equal, the catch comparison rate is 0.5 and the catch ratio is 1.0. The length-integrated average catch ratio ($CR_{average}$) value was estimated directly from the experimental catch data. Details on the estimation of $CC(l)$, $CR(l)$, and $CR_{average}$ is explained in Herrmann et al. (2017).

Further, to infer the effect of changing biodegradable snood diameter from 1.1 (A) to 1.0 (B) mm on the catch ratio curve $CR(l)$ where both catch ratio curves are obtained against the same baseline (i.e., nylon snoods with 1.0 mm diameter), the length-dependent change $CR_{A/B}(l)$ in the values was estimated by (Jacques et al., 2021):

$$CR_{A/B}(l) = \frac{CR_A(l)}{CR_B(l)} \tag{4}$$

where CR_B (l) is the catch ratio value for biodegradable snoods with 1.0 mm diameter and CR_A (l) is the catch ratio value for biodegradable snoods with 1.1 mm diameter. Efron 95% percentile CIs were obtained based on the two $CR_{A/B}$ (l) bootstrap populations of results (1000 bootstrap repetitions in each) for both CR_A (l) and CR_B (l) (Herrmann et al., 2017). As they were obtained independently, a new bootstrap population of results was created by:

$$CR_{A/B}(l)_i = \frac{CR_A(l)_i}{CR_B(l)_i} \; i \in [1 \ldots 1000] \tag{5}$$

where i is the bootstrap repetition index. As the bootstrap resampling was random and independent for the two results, it is valid to generate the bootstrap population of results for the difference based on Eq. (5) using the two independently generated bootstrap files (Herrmann et al., 2018).

2.4. Mechanical properties of the snoods

All biodegradable snoods were made of the PBSAT resin (Kim et al., 2017, patent EP3214133). Biodegradable snood line material was produced in South-Korea and manufactured by S-EnPol Ltd. The mean tensile strength of biodegradable (1.0 mm and 1.1 mm diameter separately) and nylon snood material was measured according to ASTM D2256/D2256M-21 (ASTM, 2021). The tensile strength tests were performed on new material samples that have not been used in fishery. The measurement for the mean tensile strength and elongation at break of the samples were recorded for each material type. Tensile strength, given in kilograms, is defined as the stress necessary to break the tested snood material. Elongation at break, given as a percentage relative to the initial snood sample length, is defined as the length of the sample after it has been stretched to the breaking point. The differences in tensile strength between the different materials were estimated using Welch's *t*-test (Microsoft Excel2007).

3. Results

3.1. Risk of snood line loss

Longlines with 2490 nylon snoods and 1245 biodegradable snoods with 1.0 or 1.1 mm diameter, respectively, were deployed during each fishing trip (Table 1). In total, the gear was deployed over 5 fishing trips. Snoods were considered lost when a snood together with hook was missing on the mainline (Fig. 3a) or when they were broken (Fig. 3b). The snoods were replaced in cases when a part of the hook was missing (Fig. 3c), or the snood was damaged during the fishing process (Fig. 3d).

The risk of the loss of snoods (P_{loss}) varied from 4.66% (CI: 3.84–5.46%) for nylon snoods to 6.10% (CI: 4.59–7.96%) for biodegradable snoods with 1.0 mm diameter thickness, and the rate of lost biodegradable snoods was higher compared to the nylon material (Table 1). The pairwise difference between the rates of snood losses between the material types (ΔP_{loss}) did not show statistical significance (Table 2).

Table 1
Numbers of total lost and replaced snoods over all deployments and mean risk of snood loss or need for replacement for each of the three snood line materials. Values in brackets represent 95% confidence intervals. Lost snoods were registered in cases when the snood with the hook was missing on the mainline while additional replaced snoods were registered in cases when hooks or part of the hooks were missing, or the snood was damaged during the fishing process.

	Nylon (1.0 mm diameter)	Biodegradable (1.0 mm diameter)	Biodegradable (1.1 mm diameter)
Total number of snoods in each deployment	2490	1245	1245
Total number of lost snoods over all deployments	584	378	348
Total number of replaced snoods over all deployments	175	100	88
Probability of loss (P_{loss}) (%)	4.66 (3.84–5.46)	6.10 (4.59–7.96)	5.59 (3.99–7.38)
Probability of replacement ($P_{replacement}$) (%)	1.41 (0.76–2.18)	1.61 (0.59–3.60)	1.43 (0.83–3.60)

Further, the differences in number of replaced snoods by material type and diameter ($P_{replacement}$) were recorded. No significant differences were observed for snood loss between the three snood line types as the pairwise difference ($\Delta P_{replacement}$) included 0.0 (Table 2).

3.2. Catch efficiency of biodegradable versus nylon snoods

In total, 4943 haddock and 936 cod were captured and included in the analysis of this study (Table 3). The fit statistics of the catch comparison analysis showed that the deviation between the experimental data and the modelled data fitted well in both series for both haddock and cod because p-value >0.05 (Wileman et al., 1996). This showed that the deviation between the experimental data and the modelled data could be coincidental and, therefore, the model could be used to describe the trends in the data (Table 3).

Both types of longlines in both series had a similar pattern of capturing haddock and cod regarding the fish length. For haddock, the length ranged between 31 and 78 cm and for cod it was between 31 and 111 cm total length (Figs. 4 and 5). Biodegradable snoods with both material thicknesses (1.0 and 1.1 mm) did not show significant difference in catch efficiency when compared to the nylon snoods of 1.0 mm for either haddock or cod (Figs. 4 and 5). The average catch ratio ($CR_{average}$) for both haddock and cod did not show any significant differences between use of nylon or biodegradable snoods with either 1.0- or 1.1-mm diameter of the snoods (Table 3). There was an indication of reduced capture of haddock when using 1.1 mm biodegradable material ($CR_{average} = 84.43$ (CI: 76.73–101.95)). However, this difference was not statistically significant. Moreover, the length-dependent change in catch ratio between biodegradable snoods ($CR_{A/B}(l)$) with material thickness of 1.1 mm ($CR_A(l)$) and 1.0 mm ($CR_B(l)$) did not show significant difference in capture of haddock and cod (Fig. 6).

3.3. Mechanical properties of the snood lines

The average tensile strength of the nylon snood material was 47.8 kg while for the biodegradable material it was 32.7 and 37.0 kg for snoods with 1.0 and 1.1 mm thickness, respectively (Table 4). The average elongation at break was 33.1% for nylon snoods and 31.7% and 29.3%

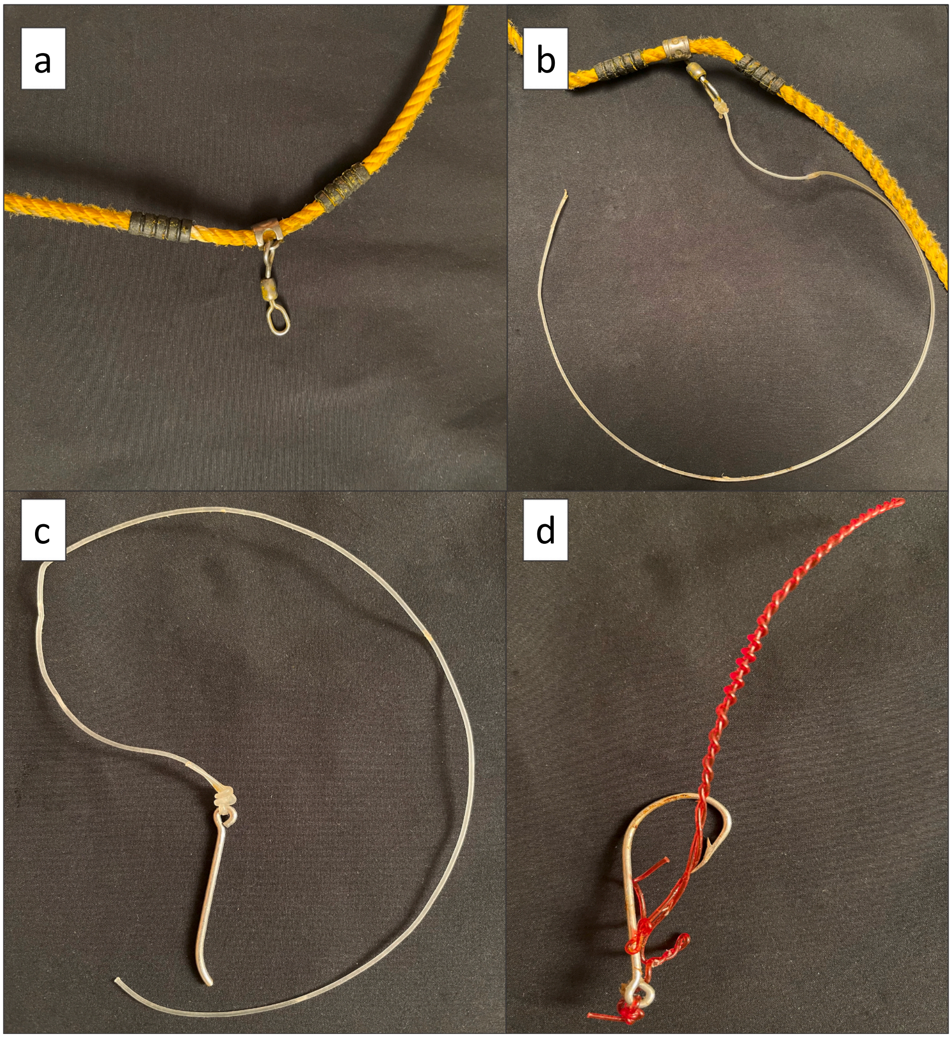

Fig. 3. Examples of cases when snoods were lost (pictures a and b) or needed replacement (pictures c and d) for the next longline deployment during rebaiting. (a) snood missing after deployment; (b) broken snood; (c) removed broken hook; (d) removed damaged snood.

Table 2
Pairwise difference (delta) between snoods of the three materials with corresponding diameters in brackets regarding risk of loss or need for replacement of the snoods. Values in brackets represent 95% confidence intervals.

	Loss (ΔP_{loss}) (%)	Replacement ($\Delta P_{replacement}$) (%)
Biodegradable (1.0 mm) against nylon	1.41 (−0.26–3.57)	0.19 (−1.28–2.27)
Biodegradable (1.1 mm) against nylon	0.26 (−0.18–0.36)	0.02 (0.00–0.04)
Biodegradable (1.1 mm) against biodegradable (1.0 mm)	−0.48 (−3.11–1.86)	−0.18 (−2.14–1.28)

for biodegradable snoods with 1.0 and 1.1 mm thickness, respectively (Table 4). There was a significant difference in the tensile strength between biodegradable snoods of both material thickness compared to nylon material (Welch's *t*-test, *p*-value <0.01). The difference was also significant when the tensile strength was compared between the two biodegradable snoods with different material thicknesses (Welch's test, *p*-value <0.01) (Table 5).

4. Discussion

In this study, we investigated whether biodegradable PBSAT materials can be used to reduce marine plastic pollution caused by lost snood lines. Specifically, we estimated the risk of snood loss, replacement, and catch efficiency when using nylon and biodegradable snood material in a longline fishery for haddock and cod. In addition, we tested whether increased biodegradable snood thickness would show different results compared to biodegradable material of equal thickness to that of nylon snoods. We aimed at estimating the initial differences between the materials, i.e., using new materials for the snoods that have not been subjected to fishing.

The estimated probability of snood loss in the coastal manually baited longline fishery for haddock and cod using nylon snoods was 4.66% (CI: 3.84–5.46%) during a longline deployment. Since the coastal longline fishery usually uses longline sets with 10.000–30.000 snood lines (Mustad autoline, 2021a), the estimated snood line loss in this longline fishery for haddock and cod would vary between 466 (384–546) to 1380 (1152–1638) snoods for each single deployment when using nylon snood lines. We found no significant increase in biodegradable snood loss during initial trials when compared to nylon snoods. The estimated biodegradable snood loss was 6.10% (CI: 4.59–7.96%) and 5.59% (CI: 3.99–7.38%) for 1.0 and 1.1 mm snood thickness, respectively. There were no significant differences regarding the estimated replacement of snoods of nylon and biodegradable material with the different thickness. However, there was an indication of increased 1.0 mm biodegradable snood loss compared to biodegradable snoods of 1.1 mm thickness and nylon snoods. These results correspond

Table 3

Fit statistics, catch comparison results and number of fish observed. Results for biodegradable snoods with 1.0 mm thickness (left column) and 1.1 mm thickness (right column) for haddock and cod. In all cases the nylon snoods with 1.0 mm thickness were used as a baseline. Values in brackets represent 95% Efron confidence limits. DOF denotes degrees of freedom.

	Haddock		Cod	
	1.0 mm diameter	1.1 mm diameter	1.0 mm diameter	1.1 mm diameter
p-value	0.0829	0.1167	0.3097	0.2700
Deviance	47.11	44.02	71.17	74.69
DOF	35	34	66	68
CRaverage (%)	89.44 (63.64–124.65)	84.43 (76.73–101.95)	91.46 (64.41–123.51)	97.53 (70.40–136.52)
Number of individuals (biodegradable snoods)	1355	949	210	237
Number of individuals (nylon snoods)	1515	1124	246	243

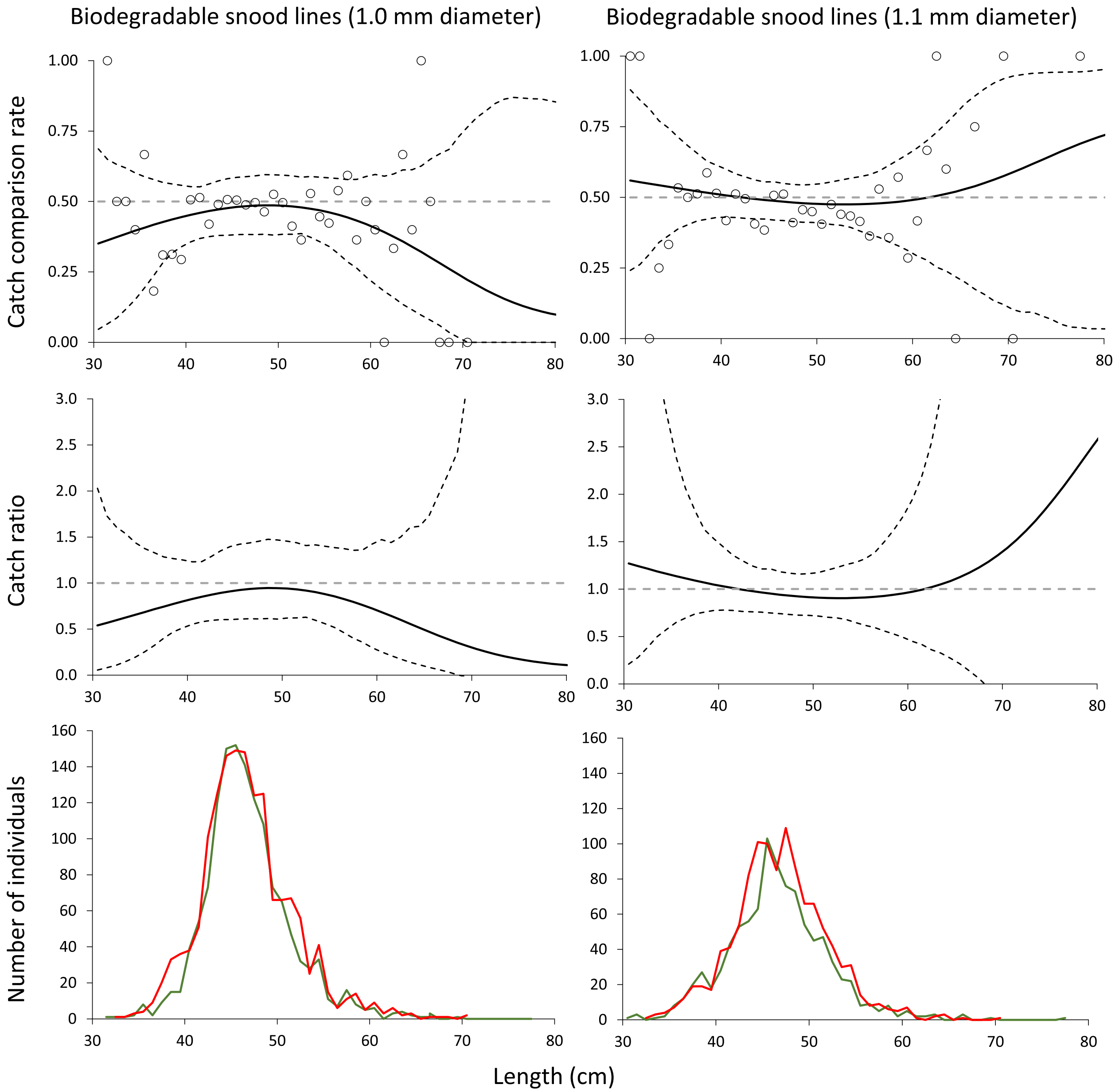

Fig. 4. Catch comparison and catch ratio analysis for haddock. Left: biodegradable snoods with 1.0 mm thickness vs nylon snoods. Right: biodegradable snoods with 1.1 mm thickness vs nylon snoods. Upper graph: the modelled catch comparison rate (black curve) with 95% confidence intervals (black stippled curves). Circles represent experimental rate. Middle: the estimated catch ratio curve (black curve) with 95% confidence intervals (black stippled curves). The grey stippled lines at 0.5 and 1.0 represent the point at which both gears have an equal catch rate. Bottom: the length frequency distribution of fish captured with the biodegradable snoods (green line) and nylon snoods (red line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

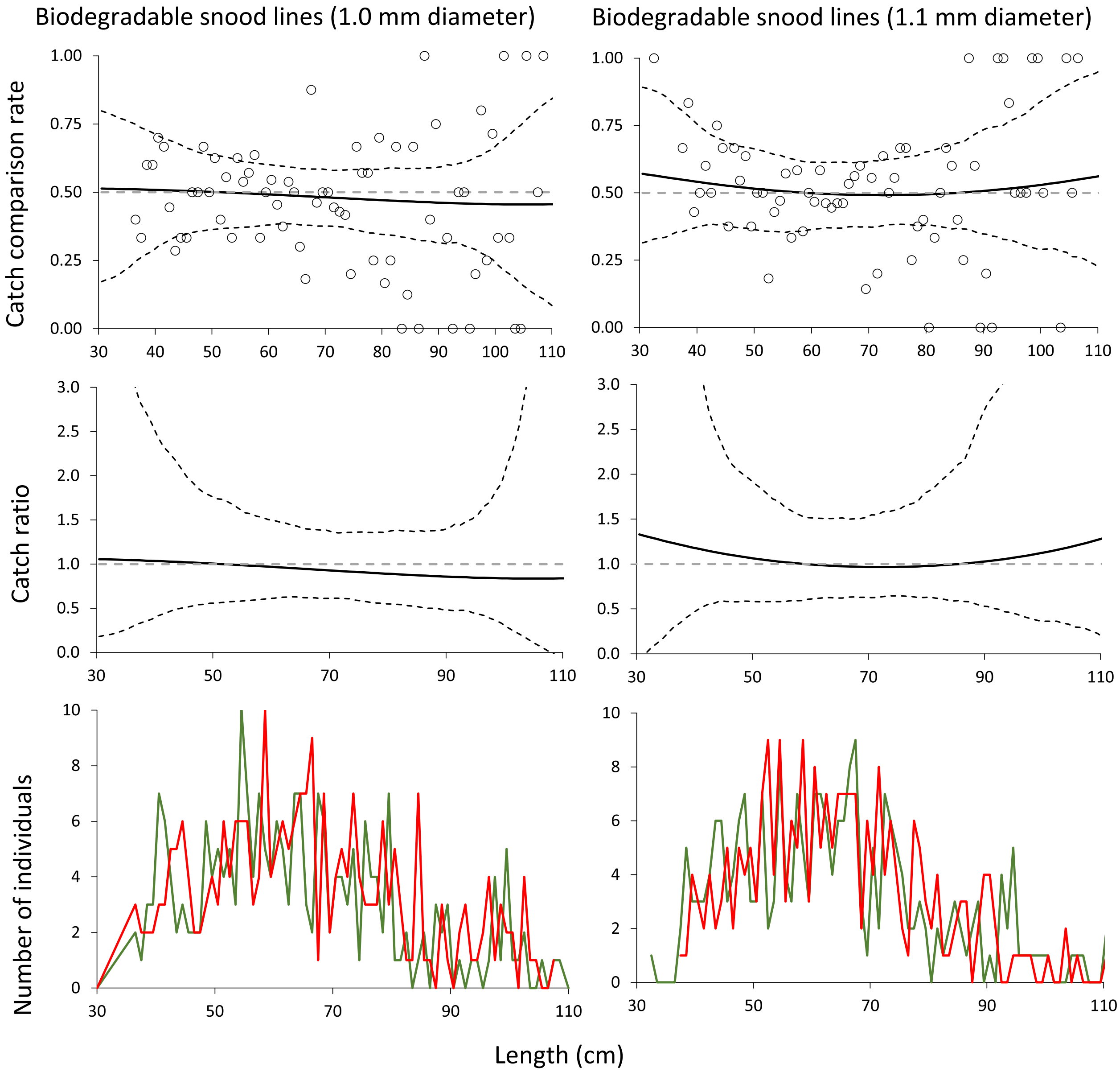

Fig. 5. Catch comparison and catch ratio analysis for cod. Left: biodegradable snoods with 1.0 mm thickness vs nylon snoods. Right: biodegradable snoods with 1.1 mm thickness vs nylon snoods. Upper graph: the modelled catch comparison rate (black curve) with 95% confidence intervals (black stippled curves). Circles represent experimental rate. Middle: the estimated catch ratio curve (black curve) with 95% confidence intervals (black stippled curves). The grey stippled lines at 0.5 and 1.0 represent the point at which both gears have an equal catch rate. Bottom: the length frequency distribution of fish captured with the biodegradable snoods (green line) and nylon snoods (red line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

with the results obtained from the material testing regarding tensile strength of the snoods. Thus, the highest estimated risk of losing the snoods is associated with the material with the lowest tensile strength, i. e., the biodegradable material with 1.0 mm thickness (mean tensile strength was 32.7 kg compared to nylon with mean breaking strength of 47.8 kg). Therefore, although not statistically significant, the results of snood loss and replacement indicate that the materials with higher tensile strength (i.e., nylon followed by biodegradable material of 1.1 mm thickness) has lower estimated risk of snood loss or replacement compared to biodegradable snoods with 1.0 mm thickness.

Further, the results showed no significant difference in catch efficiency of haddock and cod between the tested materials. Both Series 1 and Series 2 were carried out in similar conditions and the catch length dependency was also similar between the two series. No significant differences were found between fishing with snoods made of nylon and biodegradable materials. $CR_{average}$ did not show any significant differences between the snood line materials for either haddock or cod (Table 3). In addition, the results show that fishing with snoods with equal and increased twine thickness did not result in difference in catch efficiency. Specifically, in initial use of the biodegradable snoods, increasing the snood line thickness from 1.0 mm to 1.1. mm did not affect the catch efficiency when compared to conventionally used nylon snoods of 1.0 mm diameter. Moreover, the pairwise difference between biodegradable snoods on catch efficiency of haddock and cod was not significant.

Therefore, the results of this study show that use of biodegradable PBSAT material for snoods in longline fishery has a potential to reduce the marine plastic pollution. Moreover, since there are no significant differences in the estimated loss and replacement of snoods, the use of biodegradable material would not result in an increase of the associated

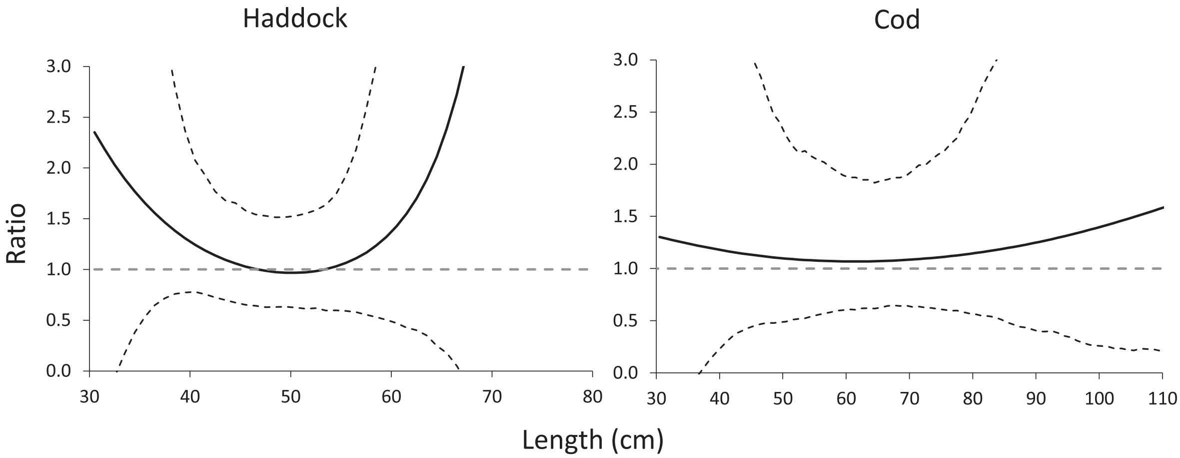

Fig. 6. Difference between biodegradable snoods of 1.0 and 1.1 twine diameters regarding catch efficiency of haddock and cod. Black line represents the estimated catch ratio curve with 95% confidence intervals (black stippled curves). Horizontal stippled line at 1.0 represents the point at which both gears have an equal catch rate.

Table 4

Mechanical properties of the snoods with corresponding diameters (in brackets). Mean values for tensile strength (kg) and elongation at break (%), with range of values (in brackets) and sample size for longlines used in the experiments.

Snood material	Elongation (%)	Tensile strength (kg)	Sample size
Nylon (1.0 mm)	33.1 (30.5–34.9)	47.8 (46.8–48.9)	3
Biodegradable (1.0 mm)	31.7 (30.6–33.1)	32.7 (32.5–32.9)	5
Biodegradable (1.1 mm)	29.3 (28.5–29.9)	37.0 (36.7–37.5)	5

Table 5

Difference in tensile strength compared by material types (Welch's t-test). Values in brackets are diameters of the material.

Compared materials	*p*-value
Biodegradable (1.0 mm) vs nylon (1.0 mm)	1.43E-03
Biodegradable (1.1 mm) vs nylon (1.0 mm)	2.00E-03
Biodegradable (1.0 mm) vs biodegradable (1.1 mm)	3.50E-07

work with replacing the snoods and loss in catch efficiency due to missing snoods and hooks during the fishing.

Because of the properties of the biodegradable PBSAT material, the lost snoods would not affect marine environment negatively even if the snoods are lost at the same quantities as with the nylon material due to biodegradation. Controlled laboratory aging test (Grimaldo et al., 2020) indicated that the chemical structure of the PBSAT polymer changed more than nylon over a 1000 h aging period (Fig. 7). The PBSAT monofilament exhibited changes in the surface in the form of degradation of the amorphous regions and the monofilament's crystalline regions. However, since aging tests are unable to replicate the outdoor conditions of field tests (i.e., temperature, light, bioactivity, and physical conditions), it was not possible to directly correlate the results of the field and laboratory tests. Grimaldo et al. (2020) concluded that it was unclear whether the fragmentation process observed in the aging test would have occurred in the marine environment or within the time needed for microbial activity to degrade the material.

It is also important to show that the new biodegradable materials do not have any negative ecotoxicological effects on the marine environment before the material is used in large scale. Generally, biodegradability is exclusively a function of the polymer structure and does not depend on the origin of the raw materials, whether they are petrochemically based or comes from renewable resources (Witt et al., 1999). Therefore, biodegradable polymers are an active area of investigation, particularly those polymers that can be produced from sustainable, biobased monomers, such as *co*polymers of polybutylene succinate (PBS) and PBS resin blended with polybutylene adipate-co-terephthalate (PBAT/PBSAT) that can be degraded by naturally occurring organisms. PBS-degrading microorganisms are widely distributed in the environment, including both actinomycetes, proteobacteria and fungi (Suyama et al., 1998; Ishii et al., 2008; Tokiwa et al., 2009). The ester linkages may be attacked by esterases and lipases in the environment (Tokiwa et al., 2009; Yamamoto-Tamura et al., 2015). MALDI-TOF analyses indicated fungal hydrolytic degradation of the ester bonds, with 10–30% mineralization during 100 days of incubation (Saadi et al., 2013). Anaerobic polyester degradation have also been reported (Pathak, 2017), while PBS degradation under anoxic conditions have not been reported. PBAT has been reported to be degraded by actinomycetes and fungi (Kijchavengkul et al., 2010; Meyer-Cifuentes et al., 2020). However, most PBAT-degrading microorganisms cannot use the monomer as carbon-source, suggesting bacterial cooperation for complete mineralization (Meyer-Cifuentes et al., 2020). Toxicology tests of aliphatic-aromatic copolyesters (i.e., Ecoflex-type) with *Dapthnia magna* and *Photobacterium phosphoreum* under conditions present in a composting system showed no significant toxicological effects, neither for the monomeric intermediates nor for the oligomeric intermediates. This study concluded that there was no indication for an environmental risk when this material were introduced into the composting processes (Witt et al., 2000).

This study was conducted with new snood materials and for a limited period and, therefore, it lacks the time dimension effect on the performance of the materials. Therefore, this study should be followed up by tests of prolonged snood use in the fishery. However, such preliminary results are important to report to investigate which material has potential to be developed to commercial use and to avoid potential replication of unsuccessful research and development work (Thabane et al., 2016). The obtained results in this study showed no initial significant differences between biodegradable and nylon snoods and the two twine thicknesses of the biodegradable material regarding estimated snood loss, need for replacement and catch efficiency. However, this difference must be estimated over repeated use under wearing of the material. Since differences in tensile strength for the biodegradable material compared to nylon are estimated to increase over time and affect the catch efficiency of the material in other fisheries (i.e., Grimaldo et al., 2020), similar processes might take place over prolonged biodegradable snood line use. This could further affect the loss of snood lines and the catch efficiency. Furthermore, currently biodegradable PBSAT materials are more expensive compared to nylon (Standal et al., 2020) which might be related to limited production since the material is still in the

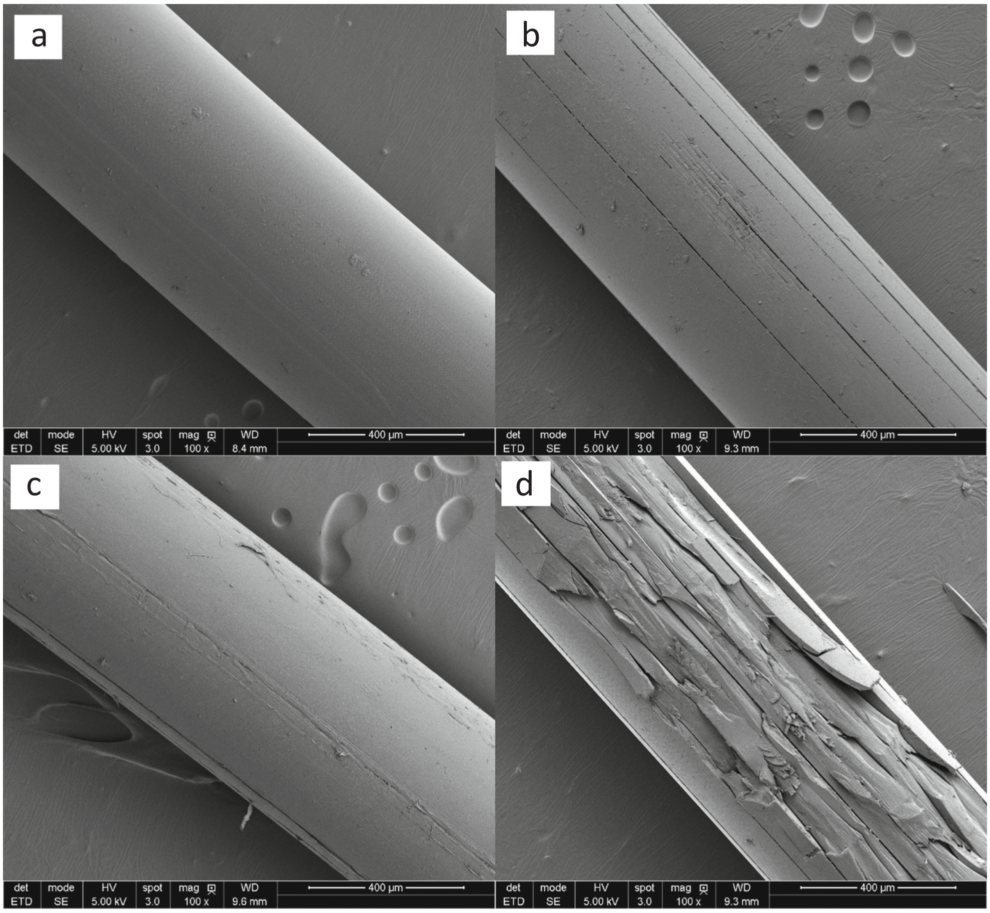

Fig. 7. Scanning electron microscope images of nylon monofilament samples (A and B images) and PBSAT monofilaments (C and D images) before (left) and after 1000 h of aging (right). Source: Grimaldo et al., 2020.

development phase. That is probably a barrier for replacement of nylon to biodegradable PBSAT snoods. However, this challenge might be overcome in time with reduction in costs if the production of the biodegradable material is scaled up and put in mass production.

CRediT authorship contribution statement

Kristine Cerbule: Conceptualization, data gathering and investigation, formal analysis, visualization, writing – original draft, writing – review and editing.

Eduardo Grimaldo: Conceptualization, writing – original draft, writing – review and editing, visualization, supervision.

Bent Herrmann: Conceptualization, software, writing – original draft, writing – review and editing, supervision.

Roger Larsen: Conceptualization, writing – original draft, supervision.

Jure Brčić: Writing – original draft, supervision.

Jørgen Vollstad: Data gathering and investigation.

Declaration of competing interest

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References

AFMA, 2010. Assessment of longline fishing in the Macquarie Island Toothfish Fishery. Available at. In: Australian Fisheries Management Authority AFTM 1300 723 621. https://www.awe.gov.au/sites/default/files/env/pages/4f27ef7d-bb8b-41ef-b8bf-ae4449de1d4d/files/afma-assessment.pdf.

ASTM, 2021. ASTM D2256/D2256M-21: Standard Test Method for Tensile Properties of Yarns by the Single-strand Method. Available at. https://www.astm.org/d2256_d2256m-21.html.

Chae, Y., An, J.Y., 2017. Effects of micro- and nanoplastics on aquatic ecosystems: current research trends and perspectives. Mar. Pollut. Bull. 124 (2), 624–632. https://doi.org/10.1016/j.marpolbul.2017.01.070.

Cole, M., Galloway, T.S., 2015. Ingestion of nanoplastics and microplastics by Pacific oyster larvae. Environ. Sci. Technol. 49 (24), 14625–14632. https://doi.org/10.1021/acs.est.5b04099.

Desforges, J.P.W., Galbraith, M., Ross, P.S., 2015. Ingestion of microplastics by zooplankton in the Northeast Pacific Ocean. Arch. Environ. Contam. Toxicol. 69 (3), 320–330. https://doi.org/10.1007/s00244-015-0172-5.

Efron, B., 1982. The jackknife, the bootstrap and other resampling plans. In: SIAM Monograph No. 38. CBSM-NSF Regional Conference Series in Applied Mathematics, Philadelphia, ISBN 978-0-89871-179-0.

Grimaldo, E., Herrmann, B., Tveit, G., Vollstad, J., Schei, M., 2018a. Effect of using biodegradable PBSAT gillnets on the catch efficiency and quality of Greenland halibut (Reinhardtius hippoglossoides). Mar. Coast. Fish. 10, 619–629. https://doi.org/10.1002/mcf2.10058.

Grimaldo, E., Herrmann, B., Vollstad, J., Su, B., Moe-Føre, H., Larsen, R.B., 2018b. Fishing efficiency of biodegradable PBSAT gillnets and conventional nylon gillnets used in norwegian cod (Gadus morhua) and saithe (Pollachius virens) fisheries. ICES J. Mar. Sci. 75 (6), 2245–2256. https://doi.org/10.1093/icesjms/fsy108.

Grimaldo, E., Herrmann, B., Vollstad, J., Su, B., Moe-Føre, H., Larsen, R.B., 2019. Comparison of fishing efficiency between biodegradable gillnets and conventional nylon gillnets. Fish. Res. 213, 67–74. https://doi.org/10.1016/j.fishres.2019.01.003.

Grimaldo, E., Herrmann, B., Jacques, N., Kubowicz, S., Cerbule, K., Su, B., Larsen, R.B. Vollstad, J., 2020. The effect of long-term use on the catch efficiency of biodegradable gillnets. Mar. Pollut. Bull. 161, 111823 https://doi.org/10.1016/j.marpolbul.2020.111823.

He, P., Chopin, F., Suuronen, P., Ferro, R.S.T., Lansley, J., 2021. Classification and illustrated definition of fishing gears. In: FAO Fisheries and Aquaculture Technical Paper No. 672. FAO, Rome. https://doi.org/10.4060/cb4966e.

Herrmann, B., Sistiaga, M., Nielsen, K.N., Larsen, R.B., 2012. Understanding the size selectivity of redfish (Sebastes spp.) in North Atlantic trawl codends. NAFO 44, 1–13. https://doi.org/10.2960/J.v44.m680.

Herrmann, B., Sistiaga, M., Rindahl, L., Tatone, I., 2017. Estimation of the effect of gear design changes on catch efficiency: methodology and a case study for a spanish longline fishery targeting hake (Merluccius merluccius). Fish. Res. 185, 153–160. https://doi.org/10.1016/j.fishres.2016.09.013.

Herrmann, B., Krag, L.A., Krafft, B.A., 2018. Size selection of Antarctic krill (Euphausia superba) in a commercial codend and trawl body. Fish. Res. 207, 49–54. https://doi.org/10.1016/j.fishres.2018.05.028.

Ishii, N., Inoue, Y., Tagaya, T., Mitomo, H., Nagai, D., Kasuya, K.-I., 2008. Isolation and characterization of poly (butylene succinate)-degrading fungi. Polym. Degrad. Stab. 93, 883–888. https://doi.org/10.1016/j.polymdegradstab. 2008.02.005.

Jacques, N., Pettersen, H., Cerbule, K., Herrmann, B., Ingólfsson, Ó.A., Sistiaga, M., Larsen, R.B., Brinkhof, J., Grimaldo, E., Brčić, J., Lilleng, D., 2021. Bycatch reduction in the deep-water shrimp (Pandalus borealis) trawl fishery by increasing codend mesh openness. Can. J. Fish. Aquat. Sci. 00, 1–11. https://doi.org/10.1139/cjfas-2021-0045.

Kijchavengkul, T., Auras, R., Rubino, M., Selke, S., Ngouajio, M., Fernandez, R.T., 2010. Biodegradation and hydrolysis rate of aliphatic aromatic polyester. Polym. Degrad. Stab. 95, 2641–2647. https://doi.org/10.1016/j.polymdegradstab. 2010.07.018.

Kim, M.K., Yun, K.C., Kang, G.D., Ahn, J.S., Kang, S.M., Kim, Y.J., Yang, M.H., Byun, K.S., 2017. Biodegradable resin composition and fishing net produced from same. US Patent application publication, US 2017/0112111A1.

Larsen, R.B., Rindahl, L., 2008. Improved catch on cod (Gadus morhua), haddock (Melanogrammus aeglefinus) and Greenland halibut (Reinhardtius hippoglossoides) with a new hauling technique in the norwegian mechanized bottom longline fishery. Fish. Res. 94 (2), 160–165. https://doi.org/10.1016/j.fishres.2008.04.008.

Larsen, R.B., Herrmann, B., Sistiaga, M., Brinkhof, J., Grimaldo, E., 2018. Bycatch reduction in the norwegian deep-water shrimp (Pandalus borealis) fishery with a double grid selection system. Fish. Res. 208, 267–273. https://doi.org/10.1016/j.fishres.2018.08.007.

Lee, K.W., Shim, W.J., Kwon, O.Y., Kang, J.H., 2013. Size-dependent effects of micro polystyrene particles in the marine copepod Tigriopus japonicus. Environ. Sci. Technol. 47 (19), 11278–11283. https://doi.org/10.1021/es401932b.

Lusher, A.L., Hollman, P.C.H., Mendoza-Hill, J.J., 2017. Microplastics in fisheries and aquaculture: status of knowledge on their occurrence and implications for aquatic organisms and food safety. In: FAO Fisheries and Aquaculture Technical Paper, 615, ISBN 978-92-5-109882-0, 126p.

Meyer-Cifuentes, I.E., Werner, J., Jehmlich, N., Will, S.E., Neumann-Schaal, M., Öztürk, B., 2020. Synergistic biodegradation of aromatic-aliphatic copolyester plastic by a marine microbial consortium. Nat. Commun. 11, 1–13. https://doi.org/10.1038/s41467-020-19583-2.

Moore, C., 2008. Synthetic polymers in the marine environment: a rapidly increasing, long-term threat. Environ. Res. 108 (2), 131–139. https://doi.org/10.1016/j.envres.2008.07.025.

Mustad Autoline, 2021. Coastal Systems. https://mustadautoline.com/products/coastal-system. (Accessed 1 April 2021).

Mustad Autoline, 2021. Deepsea Systems. Available at. https://mustadautoline.com/products/deepsea-system. (Accessed 1 April 2021).

Norwegian Directorate of Fisheries, 2021. Statistics From Fisheries 2020. Available at. https://www.fiskeridir.no/Yrkesfiske/Tall-og-analyse/Fangst-og-kvoter/Fangst/Fangst-fordelt-paa-art. (Accessed 1 April 2021).

Pathak, V.M., 2017. Review on the current status of polymer degradation: a microbial approach. Bioresour. Bioprocess. 4, 1–31. https://doi.org/10.1186/s40643-017-0145-9.

Saadi, Z., Cesar, G., Bewa, H., Benguigui, L., 2013. Fungal degradation of poly (butylene adipate-co-terephthalate) in soil and in compost. J. Polym. Environ. 21, 893–901. https://doi.org/10.1007/s10924-013-0582-2.

Standal, D., Grimaldo, E., Larsen, R.B., 2020. Governance implications for the implementation of biodegradable plastics. Mar. Policy 122, 104238. https://doi.org/10.1016/j.marpol.2020.104238.

Suyama, T., Tokiwa, Y., Ouichanpagdee, P., Kanagawa, T., Kamagata, Y., 1998. Phylogenetic affiliation of soil bacteria that degrade aliphatic polyesters available commercially as biodegradable plastics. Appl. Environ. Microbiol. 64, 5008–5011. https://doi.org/10.1128/AEM.64.12.5008-5011.1998.

Thabane, L., Hopewell, S., Lancaster, G.A., Bond, C.M., Coleman, C.L., Campbell, M.J., Eldridge, S.M., 2016. Methods and processes for development of a CONSORT extension for reporting pilot randomized controlled trials. Pilot Feasibility Stud 2, 25. https://doi.org/10.1186/s40814-016-0065-z.

Tokiwa, Y., Calabia, B.P., Ugwu, C.U., Aiba, S., 2009. Biodegradability of plastics. Int. J. Mol. Sci. 10 (9), 3722–3742. https://doi.org/10.3390/ijms10093722.

Watson, R., Revenga, C., Kura, Y., 2006. Fishing gear associated with global marine catches: IDatabase development. Fish. Res. 79 (1–2), 97–102. https://doi.org/10.1016/j.fishres.2006.01.010.

Wileman, D.A., Ferro, R.S.T., Fonteyne, R., Millar, R.B., 1996. Manual of methods of measuring the selectivity of towed fishing gears. In: ICES Cooperative Research Report, pp. 1–126.

Witt, U., Yamamoto, M., Seeliger, U., Müller, R.J., Warzelhan, V., 1999. Biodegradable polyameric materials – not the origen but the chemical structure determines biodegradability. Angew. Chem. Int. Ed. 38 (10), 1438–1442. https://doi.org/10.1002/(SICI)1521-3773(19990517)38:10<1438::AID-ANIE1438>3.0.CO;2-U.

Witt, U., Eining, T., Yamamoto, M., Kleeberg, I., Deckwer, W.-D., Müller, R.J., 2000. Biodegradation of aliphatic-aromatic copolyesters: evaluation of the final biodegradability and ecotoxicological impact of degradation intermediates. Chemosphere 44 (2001), 289–299. https://doi.org/10.1016/S0045-6535(00)00162-4.

Yamamoto-Tamura, K., Hiradate, S., Watanabe, T., Koitabashi, M., Sameshima-Yamashita, Y., Yarimizu, T., Kitamoto, H., 2015. Contribution of soil esterase to biodegradation of aliphatic polyester agricultural mulch film in cultivated soils. AMB Express 5, 1–8. https://doi.org/10.1186/s13568-014-0088-x.