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The effect of long-term use on the catch efficiency of biodegradable gillnets

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ABSTRACT

The effect of long-term use on the catch efficiency of biodegradable gillnets was investigated during commercial fishing trials and in controlled lab aging tests. The relative catch efficiency between biodegradable and nylon gillnets was evaluated over three consecutive fishing seasons for Atlantic cod (*Gadus morhua*) in Norway. The biodegradable gillnets progressively lost catch efficiency over time, as they caught 18.4%, 40.2%, and 47.4% fewer fish than the nylon gillnets during the first, second, and third season, respectively. A 1000-hour aging test revealed that both materials began to degrade after just 200 h and that biodegradable gillnets degraded faster than the nylon gillnets. Infrared spectroscopy revealed that the chemical structure of the biodegradable polymer changed more than the nylon. Although less catch efficient than nylon gillnets, biodegradable gillnets have great potential for reducing both capture in lost fishing gear and plastic pollution at sea, which are major problems in fisheries worldwide.

1. Introduction

Gillnets are among the most common fishing gears used in both developing and developed countries (FAO, 2016). These gears can be used in demersal and pelagic fisheries, from small artisanal boats to large industrial vessels. Gillnets are widely used in commercial fisheries throughout the North East Atlantic, especially by the coastal (and inshore) fleet. In Norway, the Atlantic cod (*Gadus morhua*) fishery represents the most economically important single species fishery. For the coastal fleet, gillnets account for 24% of the national total allowable catch of Atlantic cod, which in 2019 was 327,648 metric tons (NDF, 2020). In 2019, the coastal fleet consisted of 5712 vessels smaller than 27.9 m. Of these, 96% were smaller than 14.9 m (NDF, 2020) and used gillnets, as they are a very efficient, inexpensive, and easy to handle fishing gear. However, a significant proportion of gillnets are lost at sea while fishing each year despite the use of global positioning systems (GPS) for accurate gillnet localization.

Deshpande et al. (2020) provided estimates of the annual loss rates of six types of fishing gear in Norway and identified gillnets as the primary source of lost, abandoned, and/or discarded fishing gears (LADFG). Estimates from the Norwegian Directorate of Fisheries (based on reported lost gillnets) (NDF, 2019) suggest that the number is around 1000 gillnets per year, while estimates from the Norwegian Environment Agency suggest that more than 13,700 gillnets are lost each year (Sundt et al., 2018). Norway is one of the few countries in the world that has an official program to systematically retrieve lost fishing gear from high fishing pressure areas. More than 22,000 gillnets (and associated buoy lines) have been retrieved since 1983 in this program (NDF, 2019). The extent and scale of the problem increased significantly with the introduction of synthetic fibres made of polyamide 6 (PA6), better known as nylon, in the late 1950s. This was a technological advancement that increased fishing capacity and economic profitability of fisheries worldwide, similar to mechanized hauling systems, acoustic detection equipment, and GPS, among others (FAO, 2016). Synthetic gillnet materials have a high breaking strength and durability, and they are often lost in commercially important fishing grounds. Upon retrieval of lost gears, considerable amounts of fish and benthic organisms are often found inside them, which is a problem known as ghost fishing (FAO, 2016). Numerous environmental factors, such as exposure to UV radiation, wind, waves, seawater, and bacteria, affect the degradation of lost gillnets. The factors generate cracks, surface erosion, and abrasion of the material and eventually lead to its breakdown into macro-, micro-,

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and nano-sized plastic pieces (Min et al., 2020), which can impact the entire food web of an ecosystem (Lee et al., 2013; Cole and Galloway, 2015; Desforges et al., 2015; Chae and An, 2017; Lusher et al., 2017).

International recognition of the challenges posed by LADFG is demonstrated by the large number of international organizations and agreements that focus on them (FAO, 2016; GGGI, 2020; MSC, 2020). Efforts to assess the environmental impacts of LADFG are extensively documented in the literature (FAO, 2016; Hareide et al., 2005; Large et al., 2009). Several initiatives aimed at reducing the negative effects of LADFG (e.g., collection of used gillnets, measures to trace/track LADFG, and the development of biodegradable fishing gear) have gained increased attention (FAO, 2016). Over the last decade, development of biodegradable gillnets to replace traditional nylon gillnets in fisheries worldwide has increased (FAO, 2016).

Biodegradable and nylon gillnets have similar mechanical properties during fishing operations, but the biodegradable gillnets are completely degraded in seawater by naturally occurring microorganisms when dispersed in the marine environment (Tokiwa et al., 2009). Biodegradation is based on chemical-biological processes induced by treatment of the surface of the polymer with enzymes secreted by microorganisms (Ishii et al., 2008), including bacteria and fungi. This process leads to a reduction in the polymer molecular weight due to shortening of the polymer chains and elimination of their fragments. Biodegradation causes changes in both the chemical-physical properties and mechanical properties of the polymer (Razza and Degli Innocenti, 2012). Various microorganisms are known to degrade biodegradable plastics at different rates. For example, the microorganisms found in Arctic waters have a high capacity for biodegradation (Urbanek et al., 2017). Hence, replacing traditional nylon gillnets with biodegradable alternatives in this region would significantly reduce instances of ghost fishing and the production of marine plastic litter from macro- to microplastics caused by loss of non-degradable gillnets (Albertsson and Hakkarainen, 2017).

In the last two decades, biodegradable gillnets made of polybutylene succinate (PBS) resin blended with polybutylene adipate-*co*-terephthalate (PBAT) resin have been widely studied (Park et al., 2007a, 2007b, 2010; Park and Bae, 2008; Bae et al., 2012, 2013; Kim et al., 2013, 2014a, 2014b, 2016; An and Bae, 2013) and are currently being used in commercial fisheries in South Korea, China, and Japan. Since 2016, biodegradable gillnets made of polybutylene succinate *co*-adipate-co-terephthalate (PBSAT) resin have been tested in Norwegian gillnet fisheries targeting Atlantic cod, saithe (*Pollachius virens*), and Greenland halibut (*Reinhardtius hippoglossoides*) (Grimaldo et al., 2018a, 2018b, 2019, 2020). The results have shown that the catch efficiency of biodegradable gillnets is lower than that of nylon gillnets and that the mechanical properties of the materials (i.e., tensile strength, elongation at break, and elasticity) could explain the differences in catch efficiency between biodegradable and nylon gillnets (Grimaldo et al., 2018a, 2018b, 2019, 2020).

If lost, biodegradable gillnets will break down after a specific amount of time at sea and eventually disappear, thus reducing the occurrence of ghost fishing and plastic pollution at sea caused by lost gears (Brown and Macfadyen, 2007; Large et al., 2009; Macfadyen et al., 2009; Gilman, 2015; Gilman et al., 2016). Despite the potential to reduce ghost fishing and plastic pollution at sea caused by lost gears, it is important to show that the intermediate breakdown products, including those that are degradable, do not have any ecotoxicological effects on the ecosystem. Simultaneously, for biodegradable gillnets to be adopted by the industry, they should have catch efficiency comparable to that of conventional nylon gillnets and not compromise the profitability of the fishing operations.

In this study, we evaluated how the long-term use and degradation process of biodegradable gillnets affect their relative catch efficiency over time. We first assessed the relative catch efficiency of biodegradable and nylon gillnets over three consecutive fishing seasons between 2019 and 2020. These gillnets were used for approximately 1000 h in field tests, so we then conducted a controlled 1000 hour aging test to study the long-term degradation patterns of both types of material.

2. Materials and methods

2.1. Experimental gillnets

The fishing performance of 16 biodegradable gillnets and 16 conventional nylon gillnets was compared during fishing trials carried out under commercial fishing conditions. Biodegradable gillnets were made of PBSAT resin, which is an aliphatic-aromatic *co*-polyester prepared using 1.4-butanediol as an aliphatic glycol (as the base material) and dicarboxylic acids such as succinic acid and adipic acid (as the aliphatic components) and dimethyl terephthalate (as an aromatic component) (Kim et al., 2017, patent EP3214133 A1). Biodegradable and nylon gillnets were produced by S-ENPOL (Gangwon-do, South Korea). The sheets (strings) of biodegradable gillnets were made of double knotted 0.75 mm monofilament, whereas those for the nylon gillnets were made of double knotted 0.70 mm monofilament and had a similar tensile strength. Both types of gillnets had a mesh opening of 210 mm and were 30 meshes high by 275 meshes long (approximately stretched length of 55 m). Each assembled gillnet was approximately 27.5 m long with a hanging ratio of 0.5. The actual mesh sizes were measured using a Vernier calliper without applying tension to the mesh. Four rows of 20 consecutive meshes (80 meshes in total) were measured in each type of gillnet. The mean mesh size ± standard deviation of the biodegradable gillnets and nylon gillnets were 210.2 ± 1.2 mm and 206 ± 1.9 mm, respectively. To provide buoyancy, each gillnet sheet was attached to a 26 mm diameter SCANFLYT-800 floatline (made of braided polypropylene rope with a single core of polyurethane floating element inside) with a buoyancy of 150 g m^{-1}. A 16 mm diameter DANLINE leadline (made of polypropylene rope with a lead core) with a weight of 360 g m^{-1} was attached to each gillnet to provide weight. The experimental gillnets were divided into two sets, and each set consisted of eight biodegradable and eight nylon gillnets.

2.2. Sea trials and data collection

We conducted the sea trials over three consecutive fishing seasons: the January–March 2019 winter season, the October–December 2019 fall season, and the January–March 2020 winter season. The fishing trials were conducted under commercial fishing conditions on board the coastal gillnetter “MS Karoline” (10.9 m overall length). The fishing grounds were located off the coast of Troms (Northern Norway) around 69°55′–70°22′N and 19°39′–21°05′E, which is a frequently used fishing ground for coastal vessels from this region.

The two sets of gillnets used in the experiments were set approximately 1 km apart from each other. They were arranged in such a way that they provided information that could be used for paired comparison analysis (nylon (N) versus biodegradable gillnet (B)), accounting for spatial and temporal variation in the availability of cod. With individual sets being the basic unit for the paired analysis (Grimaldo et al., 2018b), it was important that the biodegradable and nylon gillnets were approximately exposed to the same spatial variability in fish availability within each gillnet set. This was achieved by alternating between the two types of nets as follows: set 1 was arranged as N-B-B-N-N-B-B-N-N-B-B-N-N-B-B-N and set 2 as B-N-N-B-B-N-N-B-B-N-N-B-B-N-N-B. The distance between each net in the gillnet set was approximately 1 m. The two sets of experimental gillnets were used in season 1 and season 2, but only one set of gillnets (set 1) was used in season 3. In total, 46 gillnet deployments were carried out during the three fishing seasons. Scientists on board the “MS Karoline” sorted the catch by type of gillnet and measured the total length (to the nearest cm) of each cod caught in all deployments. No subsampling took place.

2.3. Modelling the size-dependent catch efficiency between gillnet types

The relative catch efficiency between the two gillnet types was analysed using the statistical software SELNET (Herrmann et al., 2012, 2016; Grimaldo et al., 2018a, 2018b, 2019). We used the catch information (numbers and sizes of cod caught in each gillnet set deployment) to determine whether there was a significant difference in the catch efficiency averaged over deployments between the nylon gillnet and the biodegradable gillnet. We also tested whether a potential difference between the gillnet types could be attributed to the size (total length) of the cod. Specifically, to assess the change in relative length-dependent catch efficiency when changing from a nylon gillnet to a biodegradable gillnet, we used the method described in Herrmann et al. (2017) and compared the catch data for the two gillnet types. This method models the length-dependent (l) catch comparison rate ($CC(l)$) and catch ratio rate ($CR(l)$) summed over gillnet set deployments (for the full deployment period). The length-integrated average catch ratio ($CR_{average}$) value was estimated directly from the experimental catch data. Finally, to investigate the effect that the accumulated number of times the gillnets were deployed (DNO) had on the length-integrated catch ratio ($CR_{average}$ (DNO)) was calculated for individual deployment sets without the summation over gillnet sets. Details on the estimation of $CC(l)$, $CR(l)$, $CR_{average}$ and $CR_{average}$ (DNO) is explained in the appendix.

2.4. Mechanical properties of the gillnets

We conducted tensile testing of samples from the biodegradable and nylon gillnets used in the fishing experiments using a H10KT universal tensile testing machine (Tinius Olsen TMC, Horsham, PA, USA) equipped with a load cell with 5000 Newton rated force. The tests were performed in wet conditions on *samples* collected before the experimental fishing (at least 40 replicates for each case) according to the procedure described by the ISO 1806:2002 (ISO, 2002). We measured the mean tensile strength and elongation at break of the samples. Tensile strength, defined as the stress needed to break the sample, is given in kilograms. Elongation 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 mesh size.

2.5. Aging test

Biodegradable PBSAT and nylon monofilaments were aged during a weathering test that simulated outdoor conditions. For both monofilament types, 36 pieces of approximately 35 cm length were cut for the weathering test, yielding 72 samples in total. One set of six pieces from each material was kept aside as reference. The other pieces were fixed on to the sample holders of the weather-o-meter in groups of six. The weathering process was conducted according to ISO 4892-2 (ISO, 2013) using an Atlas Xenotest 440 weather-o-meter (Atlas Material Testing Technology, Prospect, IL, USA). The total exposure time was 1000 h, and the parameters for the weathering cycle are summarized in Table 1.

During the weathering test, one set of samples (six pieces) from each material was removed after 196, 431, 626, 817, and 1000 h for further analysis. Tensile testing of the monofilament samples was performed using a Zwick/Roell Z250 universal test machine (Zwick/Roell, 89079 Ulm, Germany), and three replicates from each set of samples were analysed following the procedure described by the ISO 1806:2002 (ISO, 2002). Infrared spectroscopy (FTIR) spectra were recorded using an Agilent Cary 670 spectrometer (Agilent Technologies, Santa Clara, CA, USA) equipped with an attenuated total reflectance (ATR) crystal. The degradation of the materials was characterized by ATR-FTIR spectroscopy, mechanical testing, light microscopy, and scanning electron microscopy (SEM).

Table 1

Weathering cycle according to ISO 4892-2 (ISO, 2013). Irradiance is the radiant flux incident on a surface per unit area. Spectral irradiance is the irradiance measured as a function of wavelength. The tolerance is indicated by ±. In the ISO 4892-2 is written "The ± tolerances given for irradiance, black-standard temperature and relative humidity are the allowable fluctuations of the parameter concerned about the given value under equilibrium conditions. This does not mean that the value may vary by plus/minus the amount indicated from the given value."

Exposure period	Irradiance UV300-400 [W/m^2]	Spectral irradiance [W/m^2 nm]	Black-standard temperature [°C]	Chamber temperature [°C]	Relative humidity [%]
102 min dry	60 ± 2	0.51 ± 0.02 (@340 nm)	65 ± 3	38 ± 3	50 ± 10
18 min water spray	60 ± 2	0.51 ± 0.02 (@340 nm)	–	38 ± 3	–

3. Results

3.1. Catch efficiency of the gillnets

In the 46 gillnet deployments carried out during the three seasons, 8679 cod were caught and included in the analysis. The accumulated weight of all of the fish was 56,924 kg. During the first season, 5330 cod were caught during 18 deployments (DNO 1–18), with 2394 individuals caught in the biodegradable gillnets and 2936 cod caught in the nylon nets. During the second season, 1293 cod were caught during 13 deployments (DNO 19–31), with 484 individuals caught in the biodegradable gillnets and 809 caught in the nylon nets. During the third season, 2056 cod were caught during 15 deployments (DNO 32–46), with 709 individuals caught in the biodegradable gillnets and 1347 caught in the nylon nets. The mean effective fishing time (the time the gillnets remained at the seabed) was 22 h 42 min, with the shortest and the longest time being 21 h 20 min and 24 h 16 min, respectively. Table 2 shows the catch data over all gillnet deployments.

The sizes of the fish caught over the three seasons had a similar structure, with most of the fish being within 85 and 110 cm. Both types of gillnets had a similar frequency tendency across length classes, but the biodegradable gillnets had a much clearer length-dependent catch efficiency than the nylon gillnets, tending to catch fewer cod of certain length classes (Fig. 1). In season 1, the biodegradable gillnets caught significantly fewer cod between 90 and 110 cm than the nylon gillnets, but for the other length classes both types of gillnets caught similar numbers of fish. In season 2, the tendency of the biodegradable gillnets to catch fewer of the larger fish was more obvious, and significant differences were found for all length classes larger than 90 cm. In season 3, a similar tendency of the biodegradable gillnets to catch significantly fewer cod of the larger length classes was observed, but this was only significant for fish between 90 and 123 cm (Fig. 1).

The $CR_{average}$ shows a clear tendency for the biodegradable gillnets to catch fewer fish over time compared to the nylon gillnets. The $CR_{average}$ was estimated to be 81.65% (CI = 75.73–87.02), 59.80% (CI = 48.06–74.21), and 52.64% (CI = 43.73–62.97) in seasons 1, 2, and 3, respectively, meaning that the biodegradable gillnets caught on average 18.35%, 40.20%, and 47.36% fewer fish than the nylon gillnets in seasons 1, 2, and 3, respectively (Table 3).

The effect of the deployment number (parameter α) on the length-integrated catch ratio showed a significant decrease (p-value = 0.00029, R^2 value = 0.1819) in relative catch efficiency for the biodegradable gillnets compared to the nylon gillnets (Table 4, Fig. 2), meaning that the accumulated number of deployments did affect the relative catch efficiency between the gillnets in a negative way.

Table 2
Catch data and information over all deployments.

Season	Set no.	*DNO*	Date (dd/mm/yyyy)	Fishing time (h: min)	Fishing depth (m) (min–max)	Number of cod in bio gillnets	Number of cod in nylon gillnets	Cod length (min–max)
1	1	1	26/01/2019	23: 14	40–115	31	39	60–125
1	2	1	26/01/2019	23: 46	48–85	14	30	62–125
1	1	2	28/01/2019	23: 05	40–115	21	31	77–113
1	2	2	28/01/2019	22: 50	48–85	41	47	71–123
1	1	3	29/01/2019	23: 10	40–115	15	20	75–114
1	2	3	29/01/2019	22: 45	48–85	7	13	81–112
1	1	4	31/01/2019	23: 30	40–115	29	37	68–118
1	2	4	31/01/2019	23: 15	48–85	13	30	76–109
1	1	5	01/02/2019	22: 55	40–115	13	20	72–109
1	2	5	01/02/2019	22: 45	48–85	5	10	89–106
1	1	6	05/02/2019	21: 55	40–115	51	54	78–120
1	2	6	05/02/2019	21: 50	48–85	97	99	78–118
1	1	7	06/02/2019	22: 50	40–115	29	55	80–110
1	2	7	06/02/2019	22: 30	48–85	74	104	71–120
1	1	8	07/02/2019	23: 05	40–115	50	49	79–122
1	2	8	07/02/2019	23: 15	48–85	55	95	65–121
1	1	9	08/02/2019	22: 45	40–115	81	107	78–121
1	2	9	08/02/2019	22: 40	48–85	107	125	75–125
1	1	10	09/02/2019	21: 45	40–115	130	133	78–116
1	2	10	09/02/2019	21: 25	48–85	112	125	64–123
1	1	11	10/02/2019	23: 20	40–115	51	77	72–122
1	2	11	10/02/2019	23: 20	48–85	67	71	79–124
1	1	12	11/02/2019	22: 50	40–115	81	100	74–125
1	2	12	11/02/2019	22: 10	48–85	27	33	81–117
1	1	13	12/02/2019	22: 10	40–115	235	285	68–120
1	2	13	12/02/2019	22: 20	48–85	186	225	68–126
1	1	14	13/02/2019	23: 00	40–115	169	213	78–122
1	2	14	13/02/2019	23: 15	48–85	88	125	74–123
1	1	15	14/02/2019	22: 00	40–115	142	157	81–121
1	2	15	14/02/2019	22: 20	48–85	107	125	74–118
1	1	16	01/01/2019	23: 15	40–115	64	71	77–123
1	2	16	01/01/2019	23: 20	48–85	73	59	68–118
1	1	18	03/03/2019	22: 30	40–115	57	73	72–121
1	2	18	03/03/2019	21: 20	48–85	72	100	79–125
2	2	19	08/11/2019	24: 16	60–78	4	7	77–100
2	1	24	23/11/2019	23: 30	40–100	4	6	85–105
2	1	26	02/01/2020	22: 45	60–120	23	31	64–110
2	2	26	02/01/2020	22: 55	78–115	14	24	74–111
2	1	27	07/01/2020	22: 50	60–120	12	29	80–118
2	2	27	07/01/2020	22: 53	48–115	40	56	69–113
2	1	28	08/01/2020	22: 59	70–120	37	40	72–115
2	2	28	08/01/2020	22: 45	68–115	47	96	77–115
2	1	29	16/01/2020	22: 06	40–115	46	62	67–123
2	2	29	16/01/2020	22: 03	48–85	60	118	72–124
2	1	30	17/01/2020	22: 30	60–110	36	70	77–118
2	2	30	17/01/2020	23: 00	58–92	42	130	79–119
2	1	31	18/01/2020	22: 02	62–110	49	47	79–112
2	2	31	18/01/2020	22: 45	48–92	70	93	81–121
3	1	32	31/01/2020	22: 05	49–105	28	46	78–115
3	1	33	01/02/2020	22: 50	68–105	28	61	69–110
3	1	34	02/02/2020	22: 30	71–92	33	72	80–123
3	1	35	10/02/2020	23: 05	80–101	103	213	80–122
3	1	36	11/02/2020	23: 15	58–85	70	94	71–119
3	1	37	12/02/2020	22: 45	54–112	39	89	82–120
3	1	38	14/02/2020	22: 40	47–85	30	59	83–125
3	1	39	15/02/2020	22: 45	63–114	9	20	88–125
3	1	40	16/02/2020	22: 25	43–85	18	47	76–125
3	1	41	17/02/2020	23: 20	75–111	15	37	87–120
3	1	42	18/02/2020	22: 20	48–85	19	43	85–123
3	1	43	19/02/2020	21: 50	71–111	95	102	82–117
3	1	44	20/02/2020	22: 10	56–85	46	98	87–118
3	1	45	21/02/2020	22: 10	66–120	133	237	81–125
3	1	46	26/02/2020	22: 45	78–114	43	129	83–122

3.2. *Mechanical properties of the new gillnets*

The average breaking strength of the new nylon netting was 21.7 kg (CI = 20.9–22.4 kg) and that of the biodegradable netting was 21.3 kg (CI = 20.7–21.9 kg). These values were not significantly different (*t*-test, *p*-value >0.01). The average elongation at break of PA netting was 40.0% (39.2–40.9%) and that of the biodegradable netting was 37.3% (CI = 37.3–37.9%). These values did differ significantly (*t*-test, *p*-value <0.01).

3.3. *Weathering of the gillnets*

Tensile testing showed considerable changes in the stress-strain curves for both the nylon and the PBSAT samples when new (non-

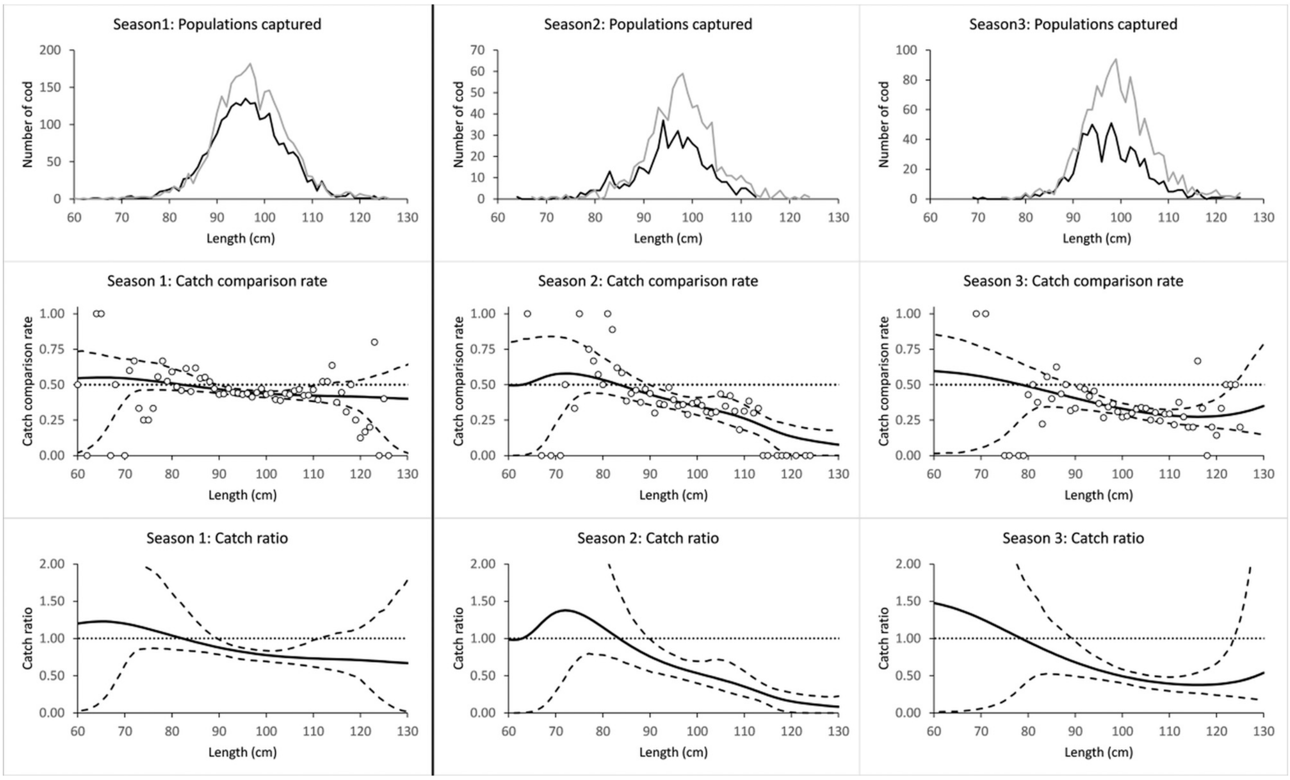

Fig. 1. Top: Length distribution of the cod population caught in each type of gillnet (the black and grey curves represent the nylon and biodegradable gillnets, respectively). Centre: Catch comparison rate *CC(l)* based on all deployments; circles represent the experimental rate and the curve represents the modelled catch comparison curve. The dotted line at 0.5 represents the baseline at which both types of gillnet have equal catch rates. The stippled curves represent the 95% confidence limits for the estimated catch comparison curve. Bottom: Estimated catch ratio *CR(l)* curve based on all deployments. The dotted line at 1.0 represents the baseline at which both types of gillnet have equal catch rates. Stippled curves represent the 95% confidence limits for the estimated catch ratio curve.

Table 3

Estimated average catch ratio ($CR_{average}$) for all fishing seasons with the fit statistics included (n, number of fish included in the analysis).

	Season 1	Season 2	Season 3
n nylon	2949	796	1347
n biodegradable	2402	476	709
$CR_{average}$ (%)	81.65 (75.73–87.02)	59.80 (48.06–74.21)	52.64 (43.73–62.97)
p-Value	0.5932	0.6331	0.5302
Deviance	54.85	43.14	45.61
DOF	58	47	47

Table 4

Results from linear modelling of the effect of number of deployments on $CR_{average}$.

Parameter	Value	Standard error	Significance (p-value)
A	−0.006622	0.001722	0.00029
B	0.819097	0.041993	< 2e−16
R^2-value	0.1819		

aged) and after 1000 h of exposure (Fig. 3); however, the strain reduction was larger for PBSAT than for nylon samples.

The strain at break decreased during aging (i.e., the material lost ductility, which is an expected sign of degradation), and this aging effect was strongest for the PBSAT monofilament samples. Fig. 4 shows the change in tensile strength and strain at break. Before aging, the tensile strength of the nylon monofilaments was significantly ($p < 0.05$) higher than that of the PBSAT monofilaments (23%). After 200 h of aging, the tensile strength of both materials started to decline, and the deterioration was strongest for PBSAT. However, after 600 h of aging, the values for the nylon samples levelled off, whereas those of the PBSAT samples continued to decline. Before aging, the elongation at break was significantly ($p < 0.05$) higher for PBSAT samples compared to nylon samples (9%), indicating that PBSAT has a slightly higher ability to deform. For both materials, the elongation at break increased slightly during the first 200 h of aging and then declined significantly. As seen for tensile strength, the elongation at break for nylon samples levelled off after about 600 h of aging, whereas that of PBSAT continued to decrease.

Light microscopy images show that both materials lost their colour quickly (Fig. 5). After just 200 h of aging, the blue colour had faded and the materials appeared faint yellow or colourless. Furthermore, cracks at the surface began to form at ~600 h of aging and were more prominent in the PBSAT samples.

SEM showed that new nylon monofilament had a smooth surface with few scratches that likely originated from the manufacturing process (Fig. 6). After 1000 h of aging, the surface of the nylon monofilament showed long cracks along the fibre axis, and the monofilament had begun to fragment, with areas that had started to fracture (Fig. 6). The surface of the new PBSAT monofilament was slightly rougher than that of the nylon, and it already exhibited some cracks along the fibre axis (Fig. 7). After 1000 h of aging, degradation of the PBSAT monofilament

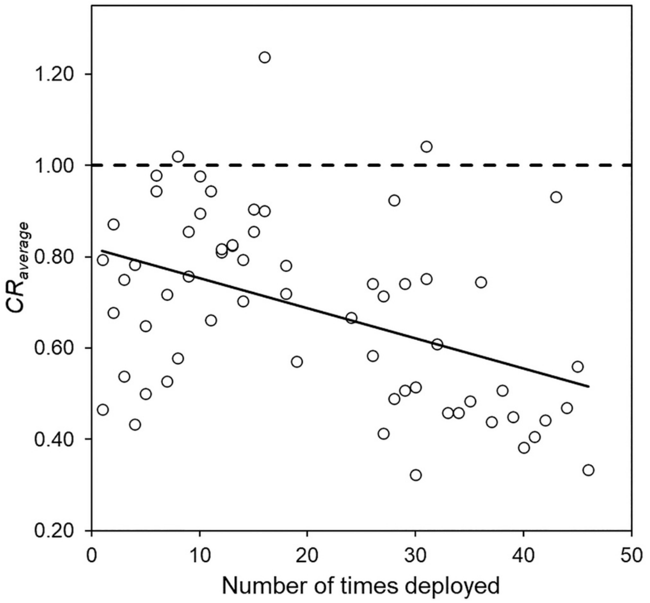

Fig. 2. Fit of the linear model (thick solid line) testing the effect of gillnet deployment frequency on $CR_{average}$. At 1.0, both biodegradable and nylon gillnets fish equally. The circle marks represent the experimental length-integrated catch ratio ($CR_{average}$) for individual deployments.

was clearly visible. The material had started to fragment, and large pieces had begun to break off from the surface (Fig. 7).

ATR-FTIR spectra of the nylon samples show that aging led to oxidation of the material, which introduced carbonyl groups that appear in the spectra as a peak at around 1730 cm^{-1} (indicated by an arrow in Fig. 8a). Otherwise, no significant changes were observed in the spectra between 0 and 1000 h. In the PBSAT samples, the main changes in the spectra during aging were the reduction of the two peaks at 1245 and 1267 cm^{-1} (stretching vibrations of Carbon–Oxygen) and the reduction of the peak at 731 cm^{-1} (bending vibration of Carbon–Hydrogen-plane of a benzene ring) (arrows in Fig. 8b). In addition, the peaks between 750 and 1200 cm^{-1} were all slightly reduced. These peaks are related to stretching vibrations of Carbon–Oxygen bonds as well as to bending vibration at the surface of adjacent hydrogen atoms on a phenyl ring. These findings indicate that the chemical structure of PBSAT changed more significantly during degradation than that of nylon.

4. Discussion

Compared to conventional nylon gillnets, the long-term use of the biodegradable gillnets negatively affected their relative catch efficiency as a consequence of degradation. Biodegradable gillnets caught on average 18.35%, 40.20%, and 47.36% fewer fish than the nylon gillnets in seasons 1, 2, and 3, respectively. Our results for catch efficiency from season 1 are highly consistent with those reported by Grimaldo et al. (2019). Both studies were carried out in similar conditions and had a similar $CR_{average}$ of around 80% compared to nylon gillnets after being

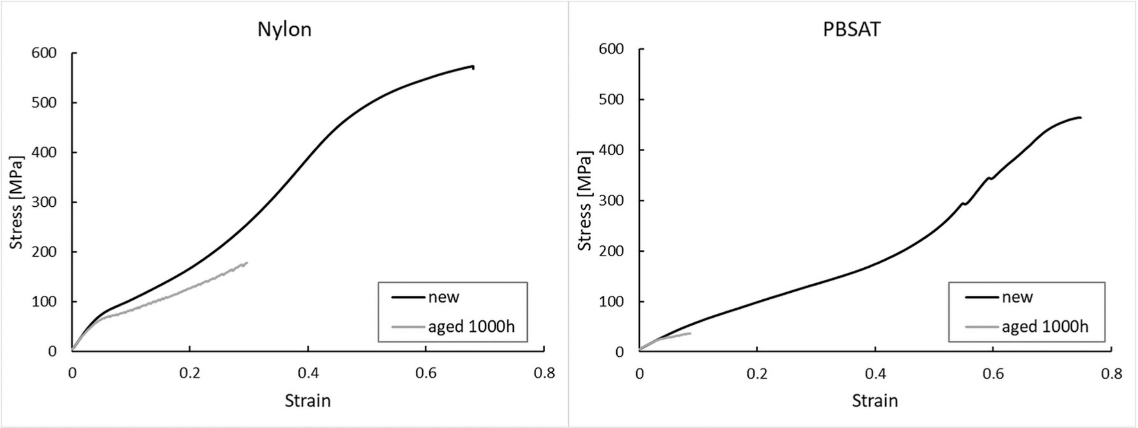

Fig. 3. Stress-strain curve of nylon (left) and PBSAT (right) samples: the strain is the engineering strain ($\Delta L/L_0$, where L_0 is the initial grip-to-grip distance), and the stress is the engineering stress (force divided by initial cross-sectional area).

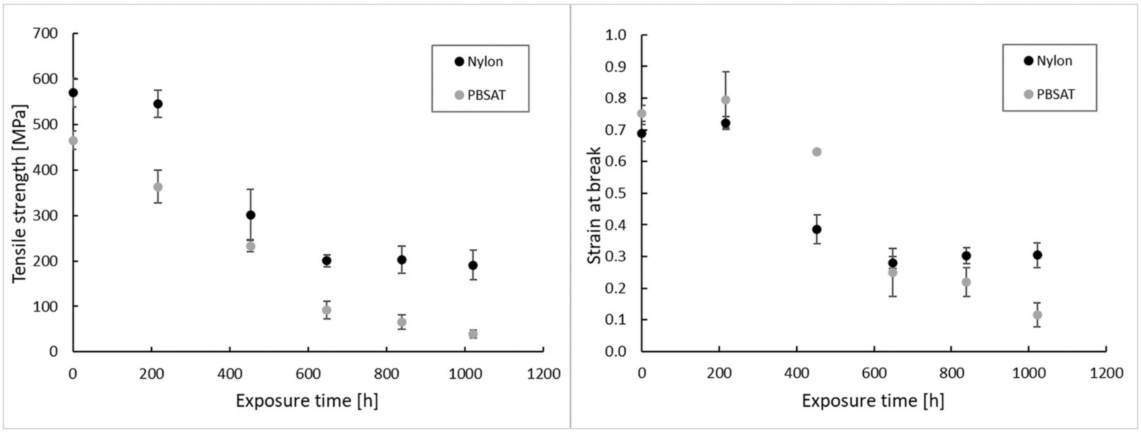

Fig. 4. The change in tensile strength (left) and strain at break (right) during aging. The dots are mean observations and the bars are the standard error.

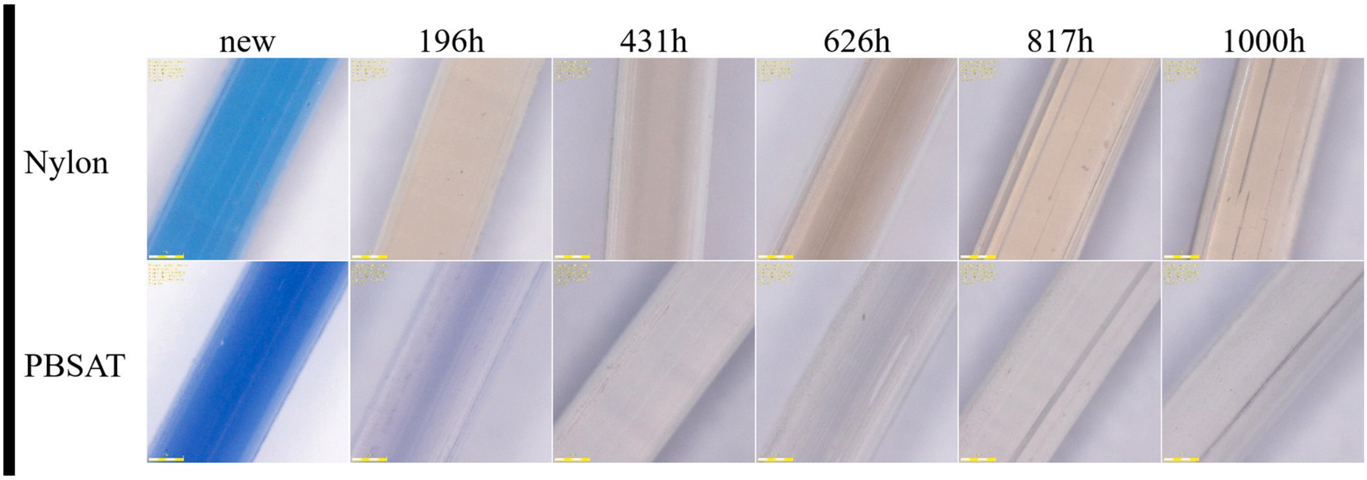

Fig. 5. Light microscopy images of nylon and PBSAT samples at different time points during the aging test.

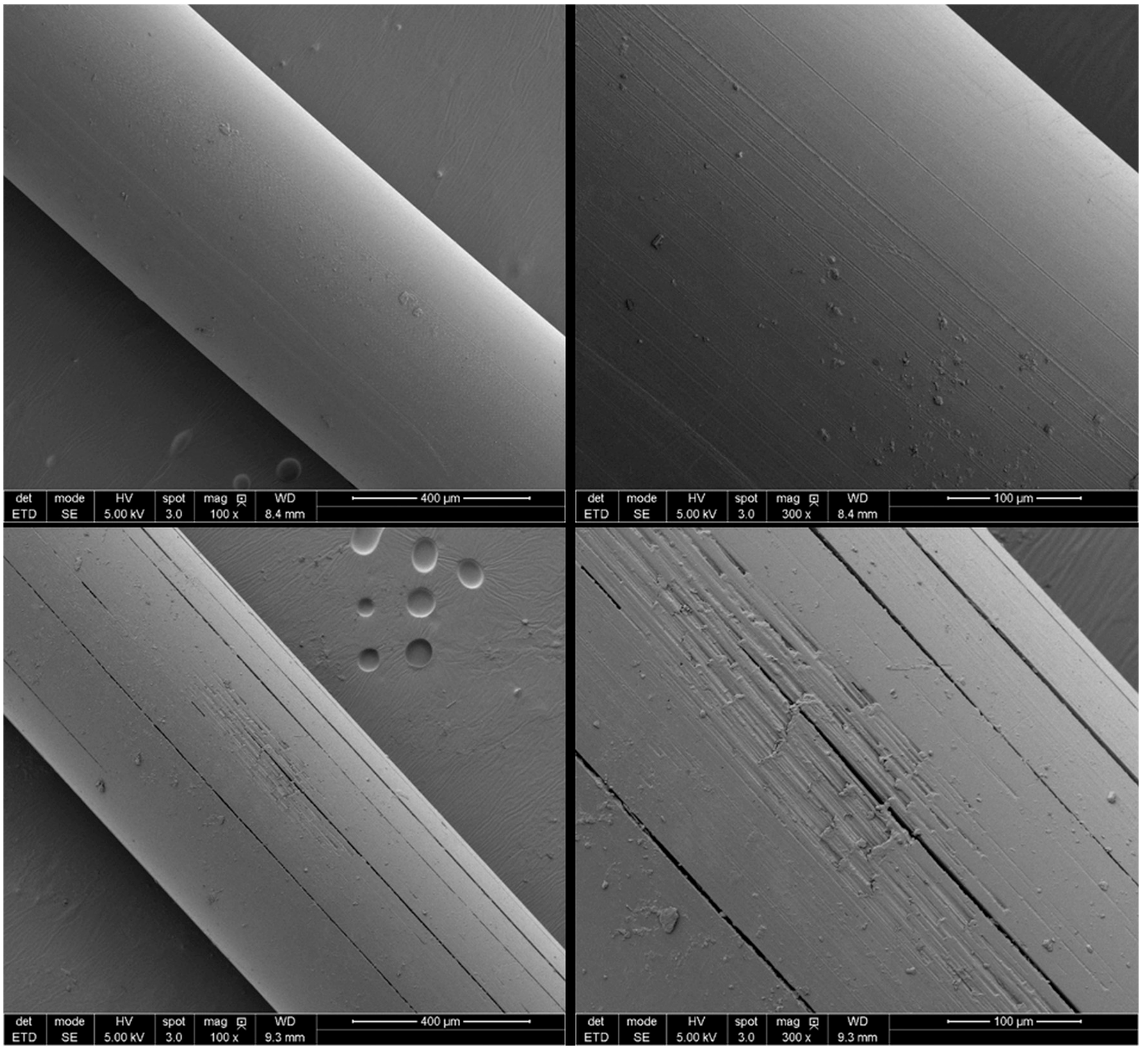

Fig. 6. SEM micrographs of the nylon monofilament samples before (upper images) and after 1000 h of aging (lower images).

used for one fishing season. The catch length dependency in the two studies also was similar, as significantly more fish of the largest length classes (> 90 cm) were caught by the nylon gillnets. These results show that fishing with equally strong gillnets (in terms of tensile strength) did not yield similar catch patterns. In other words, increasing the monofilament thickness of biodegradable gillnets from 0.70 mm to 0.75 mm to match the tensile strength of the 0.70 mm nylon monofilaments did not yield similar catch efficiency or length distribution of fish in the

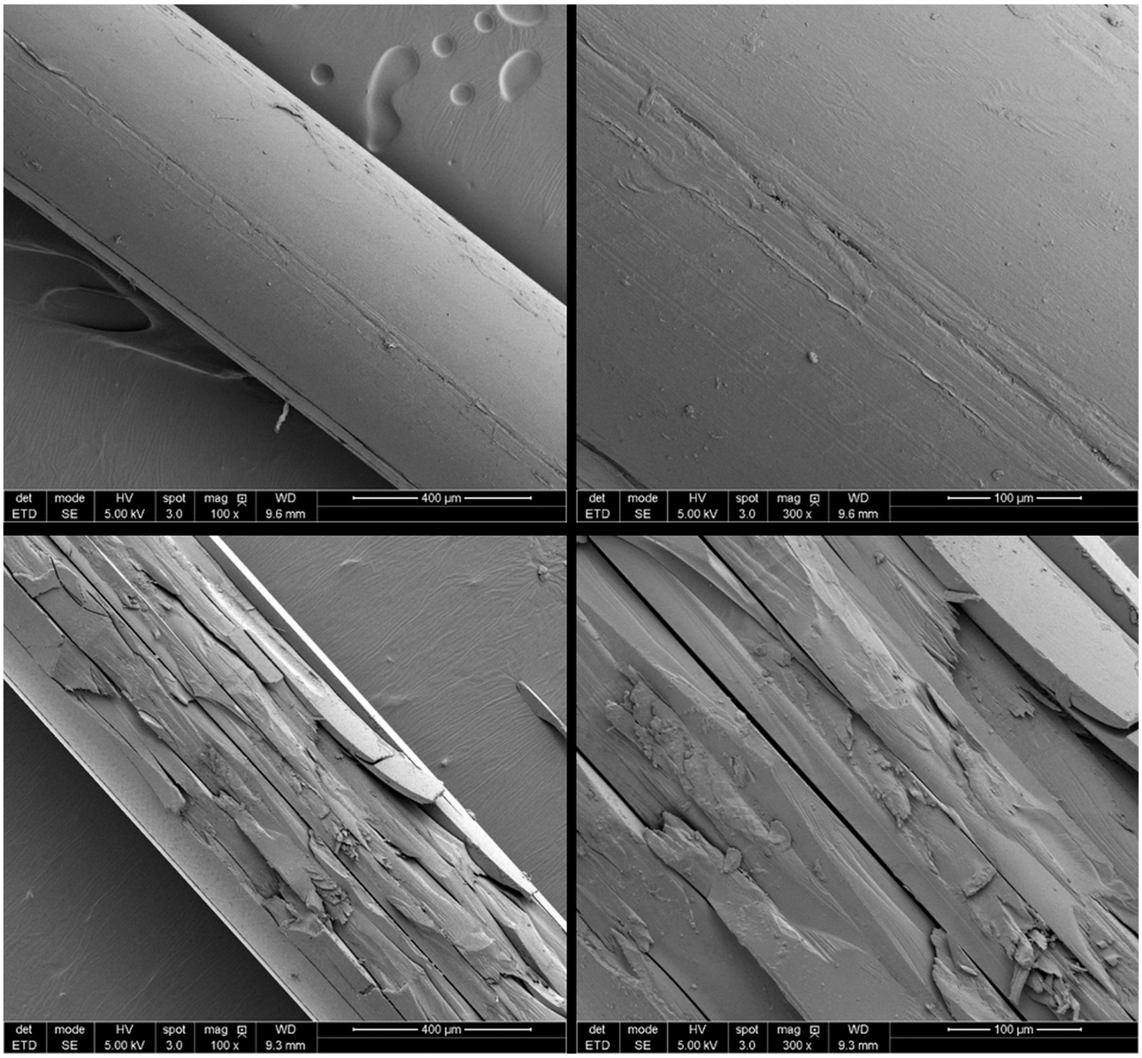

Fig. 7. SEM micrographs of the PBSAT monofilament before (upper images) and after 1000 h of aging (lower images).

catch. Our results and those reported by Grimaldo et al. (2018b, 2019, 2020) suggest that tensile strength may not be responsible for the catch profiles of the biodegradable gillnets and that other mechanical properties (i.e., elasticity) may have a stronger effect on the catch performance of the biodegradable gillnets. Lower catch rates (0.6–0.9) and slightly different catch profiles of biodegradable gillnets compared to nylon gillnets have also been observed in other fisheries, such as flounder (*Cleisthenes pinetorum*) (Bae et al., 2013), yellow croaker (*Larimichthys polyactis*) (Kim et al., 2016), and Greenland halibut (Grimaldo et al., 2018a), and these differences have been attributed to mechanical differences between the two types of gillnets.

The prolonged use (three seasons) of the gillnets caused a dramatic reduction of the relative catch efficiency of the biodegradable gillnets. The $CR_{average}$ dropped from 81.65% to 59.80% from season 1 to season 2 and further to 52.64% in season 3. This large reduction in catch efficiency can be explained by the degradation process acting in the biodegradable material. Kim et al. (2016) found that biodegradable gillnets show considerable degradation after 2 years and that almost full degradation of this gillnet material was expected after 4 to 5 years. Nylon gillnets also showed a certain reduction of catch efficiency, likely due to degradation processes that affected the mechanical properties of the material. The deterioration of biodegradable and nylon gillnets our study was the result of chemical changes that occurred in the structure of the polymers during the three-season experimental period (approximately 14 month duration). Different mechanisms of degradation may have acted simultaneously on the biodegradable and nylon fibres, and some probably had a stronger effect than others. Although we were unable to identify, isolate, and quantify the effects of specific mechanisms of degradation on the gillnets in the field experiment, possible mechanisms were microbiological degradation, hydrolysis, oxidation, and mechanical damage (e.g., abrasion in the hauling machine, friction due to contact with hard surfaces when the gillnets were operated on deck). Polymers are also known to be vulnerable to UV exposure, but this was not in effect in our field experiments, which were conducted during the polar night period in northern Norway. However, we did not have control over the storage conditions of the gillnets between the seasons. Specifically, the 6 month interval between season 1 (January–March) and season 2 (October–December), when the biodegradable gillnets suffered a large catch efficiency reduction, was the polar summer (long periods of daylight). If the gillnets were stored outdoors during this time, the nets may have suffered intense damage from UV exposure. Furthermore, bacterial and thermal degradation processes may have continued to act on the biodegradable gillnets during storage. Physical damage caused by use and wear of the gillnets may have also contributed to the degradation of the nylon and biodegradable gillnets and consequently to the reduction of their fishing capacity. The effects of use and wear is, however, were confounded in the analysis and we were unable to isolate their effects on catch efficiency of the nets.

The controlled laboratory aging test provided an indication of how the materials degrade over time. Changes in the chemical structure of

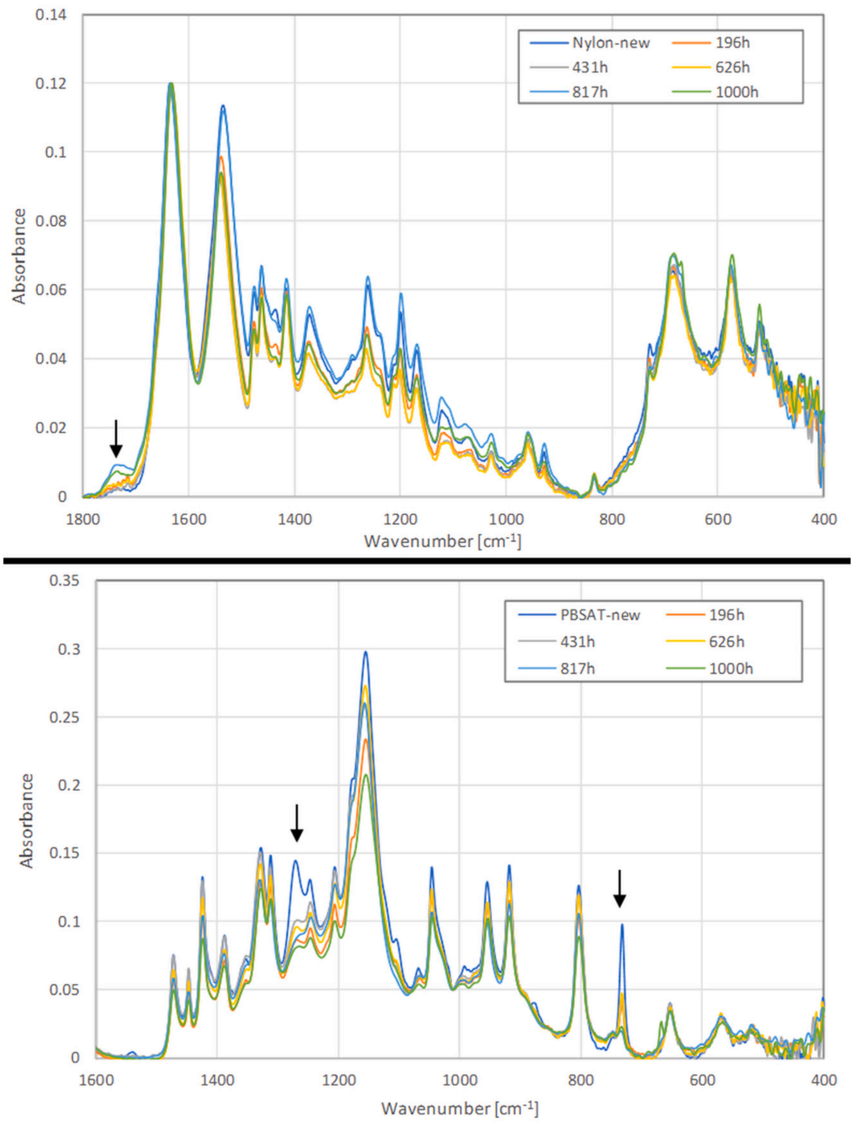

Fig. 8. ATR-FTIR spectra of nylon (top, a) and PBSAT (down, b).

the materials were apparent after 1000 h of aging. The biodegradable PBSAT monofilament exhibited radical changes in the surface of the monofilament in the form of degradation of amorphous regions and the monofilament's crystalline regions as well as fragmentation. The ATR-FTIR spectra of the biodegradable PBSAT samples (Fig. 8) show that the main changes in the spectra during aging were the reduction of the two peaks at 1245 and 1267 cm^{-1} (stretching vibrations of C—O) and the reduction of the peak at 731 cm^{-1} (bending vibration of CH-plane of a benzene ring). The peaks between 750 and 1200 cm^{-1} also were slightly reduced. These peaks are related to stretching vibrations of C—O bonds and to bending vibration at the surface of adjacent hydrogen atoms on a phenyl ring. Our findings indicate that the chemical structure of the PBSAT polymer changed more significantly during degradation compared to that of the nylon. Because the aging test was unable to replicate the outdoor conditions of the field tests (i.e., temperature, light, bioactivity, and physical conditions), we are not able to directly correlate the results of the field and laboratory tests. It remains 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. Although the laboratory aging test allowed us to quickly assess the relative stability of the plastics under defined controlled conditions, the major disadvantage of this method is that shorter duration tests mean lower correlation to real behaviour in the field. Nonetheless, the two studies complemented each other, as they provided a detailed picture of the degradation behaviour occurring in both gillnet types and the effect of degradation on the catch pattern. Grimaldo et al. (2018a, 2018b, 2019, 2020) previously evaluated tensile strength of gillnets, but their trials did not provide information about changes in the mechanical properties between fishing seasons or about how quickly degradation of the material affects the catch efficiency of the gillnets. Our chemical and SEM analyses provided an in-depth assessment of the degradation process that helped us better interpret the fishing trial results. In addition, SEM analysis provided information about the changes on the surface of the monofilaments, which is relevant to understanding particle formation (micro-plastics) due to degradation and fragmentation of the monofilaments.

If biodegradable gillnets are lost during the fishing season, bacteria, algae, and fungi will degrade the twines over time. Because the biodegradable materials are degraded into carbon dioxide, methane, and water, they do not have any negative impact on the marine ecosystem (Kim et al., 2014a, 2014b). In the case of nylon gillnets, weakening of the material due to use and wear almost stops when the gear is lost, and the degradation process of the material then continues very slowly. It is well documented that nylon gillnets are highly resistant to degradation and that they eventually lose their ability to ghost fish depending on the conditions of the seafloor (Carr et al., 1990; Humborstad et al., 2003; Pawson, 2003; Santos et al., 2003; Tschernij and Larsson, 2003; Nakashima and Matsuoka, 2004; Pham et al., 2014). Furthermore, nylon gillnets do not disappear entirely; they just degrade into smaller plastic particles that may continue to disturb various processes in the marine ecosystem (Moore, 2008). According to Kim et al. (2016), biodegradable PBS-PBAT gillnets stop catching fish (i.e., ghost fishing) after 2 years of being immersed in seawater, and our results support these findings. Our experiment last for 14 months and after that period of time the biodegradable gillnets were 47.36% weaker than new nets; thus, a projection of the degradation trend and reduction of tensile strength would show very weak monofilament strength after two years of immersion.

The lifespan of gillnets, which we define as the period in which they can be used for fishing, depends greatly on their durability and the degree of damage that they suffer when fishing. In the Norwegian gillnet fishery for Atlantic cod, a conventional nylon gillnet is usually used for one season. One season normally lasts between 2 and 4 months depending on the boat, the quota, fish availability, and catch efficiency. After the end of the fishing season, fishermen normally exchange the sheets (string) of nets for new ones because the cost of repairing the nets is much greater than the cost of buying relatively non-expensive nylon gillnets. In these circumstances, the use of short lifespan biodegradable gillnets could easily be an alternative to conventional nylon gillnets without representing a large investment for the fishermen, as long as the profitability of fishing operations is not compromised. However, the results of fishing trials consistently show 10–40% lower catch efficiencies for biodegradable gillnets than for nylon gillnets (Bae et al., 2013; Kim et al., 2016; Grimaldo et al., 2018a, 2018b, 2019, 2020).

In conclusion, our results show how quickly biodegradable gillnets lose their fishing efficiency due to degradation and also reaffirm their potential for use as a feasible alternative to conventional nylon gillnets. In short season fisheries such as that for Atlantic cod, biodegradable gillnets would significantly reduce the effect of unaccounted for mortality and marine plastic pollution if gillnets are lost (i.e., ghost fishing, microplastics). However, the reduction of the catch would negatively impact the cost-effectiveness of the fishing operation and the acceptance of biodegradable gillnets by fishermen. Management challenges such as how to provide incentives to promote the use of less efficient biodegradable nets should be addressed.

CRediT authorship contribution statement

Eduardo Grimaldo: Conceptualization, Investigation, Writing - original draft, Writing - review & editing, Funding acquisition. **Bent Herrmann:** Formal analysis, Investigation, Writing - original draft, Writing - review & editing. **Nadine Jacques:** Investigation, Writing - original draft, Writing - review & editing. **Stephan Kubowicz:** Investigation, Writing - review & editing. **Kristine Cerbule:** Investigation, Writing - original draft, Writing - review & editing. **Biao Su:** Investigation. **Roger Larsen:** Writing - original draft. **Jørgen Vollstad:** Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Details on modelling the size-dependent catch efficiency between gillnet types can be downloaded as supplementary material from the online version. Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2020.111823.

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