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FEATURE PAPER

Use of biodegradable driftnets to prevent ghost fishing: physical properties and fishing performance for yellow croaker

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ghost fishing; biodegradable; driftnet fishing; fishing nets; polybutylene succinate; yellow croaker.

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Abstract

When synthetic non-biodegradable fishing nets are lost, abandoned or discarded at sea, they may continue to catch fish and other animals for a long period of time. This phenomenon is known as ‘ghost fishing’. Biodegradable fishing nets, on the other hand, are intended to degrade or decompose after a certain period of time under water and thereby lose their ghost fishing capacity more quickly than conventional gear. A biodegradable net material, a blend of 82% polybutylene succinate (PBS) and 18% polybutylene adipate-co-terephthalate (PBAT), was developed. We examined the physical properties and degradability of the biodegradable monofilament, and compared the fishing performance of driftnets made of conventional nylon and of the biodegradable material. When dry, conventional nylon monofilament exhibited a greater breaking strength and elongation than biodegradable monofilament of the same diameter. When wet, the biodegradable monofilament exhibited a stiffness of *c.* 1.5-fold than nylon monofilament. This suggests that a net made of the less flexible biodegradable monofilament would have lower fishing efficiency than conventional nets. The fishing performance comparisons between the biodegradable and conventional nylon nets, however, revealed similar catch rates for yellow croaker *Larimichthys polyactis*. Biodegradable monofilament started to degrade after 24 months in seawater by marine organisms. We conclude that biodegradable netting may become a feasible alternative to conventional nylon netting and can contribute to reducing the duration of ghost fishing. Nonetheless, there remain many uncertainties, challenges and knowledge gaps that have to be solved before we are able to draw firm conclusions about the overall benefits of these materials in driftnet fisheries.

Introduction

A wide variety of materials are available to manufacture fishing nets. Until the early 1960s, natural materials such as cotton and hemp were commonly used. With the advent of polyamide-based nylon after World War II, synthetic fibers quickly replaced natural materials (von Brandt, 1984). The excellent fishing performance, high strength and low price of synthetic materials contributed to the development of worldwide gillnet and driftnet fisheries (Anonymous, 1990; Wright & Doulman, 1991; Richards, 1994).

The major drawback of synthetic nets is that they are very resistant to degradation once they have been lost, abandoned or discarded at sea. This derelict fishing gear may ghost fish, where the abandoned, lost or otherwise discarded fishing gear (ALDFG) continues to catch fish and other animals (Kaiser *et al.*, 1996; Erzini *et al.*, 1997; Humborstad *et al.*, 2003; Pawson, 2003; Revill & Dunlin, 2003; Santos *et al.*, 2003; Tschernij & Larsson, 2003; Ayaz *et al.*, 2006; Baeta, Costa & Cabral, 2009). Ghost fishing may trigger a vicious circle of fish and other marine organisms being caught in derelict nets, dying and acting as bait that lures in other organisms. These ghost fishing losses are undesirable for socioeconomic and conservation reasons.

Abandoned, lost or otherwise discarded fishing gear from net fisheries may also entangle and kill larger marine animals and sea birds, disturb spawning grounds and smother habitats, thereby serving as major hazards and a long-term threat in marine environments (Sheldon, 1975; High, 1976; Matsuoka, Nakashima & Nagasawa, 2005; Gilman *et al.*, 2013; Wilcox *et al.*, 2013). Furthermore, synthetic fishing nets which by the time have weathered and fragmented into smaller particles at sea will eventually accumulate in marine ecosystems and may have significant biochemical long-term effects on marine biota (e.g. Moore, 2008).

The ecological and socioeconomic problems caused by ALDFG are an increasing global concern and have attracted significant worldwide attention (e.g. IMO, 1978; Anonymous, 1990; Wright & Doulman, 1991; Richards, 1994; Macfadyen, Huntington & Cappel, 2009; FAO, 2011; UNEP & NOAA, 2012; Gilman, 2015). Since 2004, several United Nations General Assembly (UNGA) Resolutions have explicitly recognized problems resulting from ALDFG and called upon states and international organizations to take steps to mitigate these problems (e.g. UNGA, 2004, 2014). On its 31st Session, the FAO Committee on Fisheries expressed concern over ghost fishing by ALDFG and noted that greater attention should be paid to mitigate ALDFG impacts (FAO, 2014).

The types of fishing gears that most frequently cause ghost fishing are drift gillnets (driftnets), set (anchored) gillnets, trammel nets, pots and traps because they are widely used and frequently lost or abandoned at sea. Because driftnets, set gillnets and trammel nets are made from thin and elastic twines, they readily entangle on various objects in the sea and have a large capacity to catch various types of organisms. From the ghost fishing point of view, driftnets, trammel nets and set gillnets are likely the most problematic component of ALDFG.

There have been substantial efforts to understand the characteristic, quantity and impact of ghost fishing, and to find solutions for reducing negative impacts (Matsuoka *et al.*, 2005; Ayaz *et al.*, 2006; Brown & Macfadyen, 2007; Baeta *et al.*, 2009; Campbell & Sumpton, 2009; Anderson & Alford, 2014; Kim, Lee & Moon, 2014*a*; Gilman, 2015). Through these efforts it has become obvious that structural design features on specific gear components may markedly help to reduce ghost fishing in particular in trap-net and pot fisheries, but are less likely to be as feasible in driftnet, trammel net and set gillnet fisheries (e.g. Suuronen *et al.*, 2012). In the case of driftnet, trammel net and set gillnet fisheries, a promising option to reduce ghost fishing of ALDFG is to use biodegradable twine materials that decompose in seawater due to fungal or microbial organisms.

In Korea (Republic), a manufacturing method for fishing nets has recently been developed that uses biodegradable resin which can be decomposed by microbial action (bacteria and fungi) after a certain amount of time underwater. Various experiments and tests, using biodegradable resin-based materials, have been conducted to find biodegradable nets with appropriate properties for driftnets and traps (Park *et al.*, 2007*a*,*b*, 2010; Kim, Park & Lee, 2014*b*,*c*). It is noteworthy that in Korea it is estimated that 38 535 tons of various types of gillnets are annually lost or discarded (Kim *et al.*, 2014*a*).

The current study was conducted to assess the physical properties and the commercial viability of a biodegradable resin-based monofilament net.

Materials and methods

Characteristics of biodegradable monofilament

The biodegradable monofilament was produced using a resin blend of 82% polybutylene succinate (PBS) and 18% polybutylene adipate-co-terephthalate (PBAT).

Polybutylene succinate is biodegradable aliphatic polyester that is produced by polycondensation of 1,4-butanediol with succinic acid (Doi *et al.*, 1996; Bhari *et al.*, 1998). It has high flexibility, breaking strength and thermal and chemical resistance. Its specific gravity is 1.24 and melting point is 114°C (Fujimaki, 1998; Park *et al.*, 2010).

Polybutylene adipate-co-terephthalate is an aliphatic, co-aromatic, co-polyester blend synthesized through the esterification of 1,4-butanediol with aromatic dicarboxylic acid and polycondensation with succinic acid. PBAT offers several advantages over other biodegradable materials due to its flexibility, excellent impact strength and low melting point. PBAT exhibits significant biodegradation within 1 year in soil, water with activated sludge and seawater (Uwe, Rolf-Joachim & Wolf-Dieter, 1995; Witt, Müller & Deckwer, 1996, 1997; Rantze *et al.*, 1998). The blending rate was developed to make use of the different physical properties of PBS and PBAT resins to yield the optimal strength and flexibility required for driftnets.

Within 2 years of being submerged in seawater, the monofilament spun by polymerizing the PBS and PBAT is degraded by microorganisms (Ishii *et al.*, 2008), resulting in low-molecular-weight oligomers, dimers and monomers, and finally is mineralized into CO_2 and H_2O in seawater (Tokiwa *et al.*, 2009).

Property testing of biodegradable monofilament

To determine and compare the physical properties of the biodegradable and conventional nylon monofilaments, their breaking strength (tensile strength at break) and elongation at break were measured. These measurements were made in compliance with the ASTM D638 using a universal testing machine (Instron 3365; Norwood, MA, USA) in 1/1000 g increments per 0.1 s. The distance between the clamps for holding the monofilament in the tensile test was set at 400 mm, and the ultimate breaking strength and elongation at break were measured for 20 replicates at the moment in which they separated. The physical properties of the monofilaments were tested on both knotless and knotted (single knot) monofilaments, considering that nets are constructed with knots. When testing the knotted monofilament, it was placed so that a knot was centered between the clamps of the universal tester. The measurement results were then stored as input data.

Flexibility (the opposite of stiffness) of the monofilament was measured with the Brandt's method (Andres & Garrother, 1964; Kim *et al.*, 2014*c*), whereby the experimental line was prepared for testing by evenly winding the monofilament 20 times on a cylindrical core (Ø 4 cm), followed by unwinding. When measuring the flexibility, the load was measured at the moment when the nylon and biodegradable monofilaments were compressed to 2.5 cm (Fig. 1).

The load cell used in the stiffness test apparatus had a maximum capacity of 0.1 N (DH Tech-1, Busan, Korea). The measurement data were relayed to the amplifier (SENTECH-20, Busan, Korea) and stored at 15 s sampling intervals. Testing

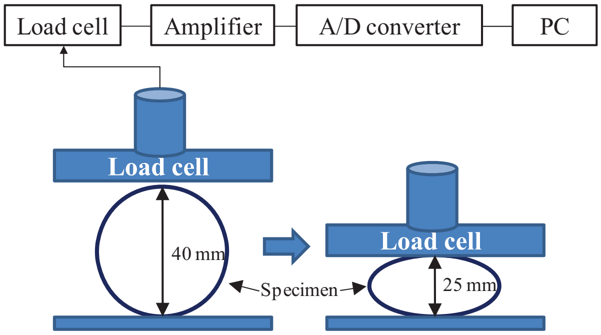

Figure 1 A schematic concept for measuring the stiffness of the monofilaments by Brandt's method.

was performed in dry and wet conditions, with 20 replicates for each condition, at the compression application rate of 2 mm s^{-1} in a laboratory environment under constant temperature (20 ± 2°C) and relative humidity (65 ± 2%). The pieces of experimental line to be tested, while wet, were prepared by immersion in distilled water for 24 h.

Experimental gear design

To measure the fishing performance of biodegradable net, experimental driftnets were manufactured using the same design and dimension as in commercial driftnets targeting yellow croaker *Larimichthys polyactis* in the southwestern coastal areas of Korea. Yellow croaker driftnet fishing was selected in these experiments because this is a very common fishery in Korea and because there is frequent loss of nets in this fishery (Kim *et al.*, 2013, 2014*a*). In general, a driftnet is a type of gillnet that is set in water so that is can drift freely. A yellow croaker driftnet, however, is installed near the sea bed so that it almost touches the bottom. The net moves along with the current and that is why the net is called a driftnet. These nets are often lost due to entanglement on reefs or other submerged features. Nets also often get entangled with each other, another cause of gear loss in this fishery.

The biodegradable and conventional nylon nets used in the comparative fishing trials had the same dimensions and designs (Fig. 2a). The nets had 300 vertical and 1050 horizontal meshes with a 51-mm mesh size (stretched inner full mesh). The float line was 24.5-m long and consisted of two

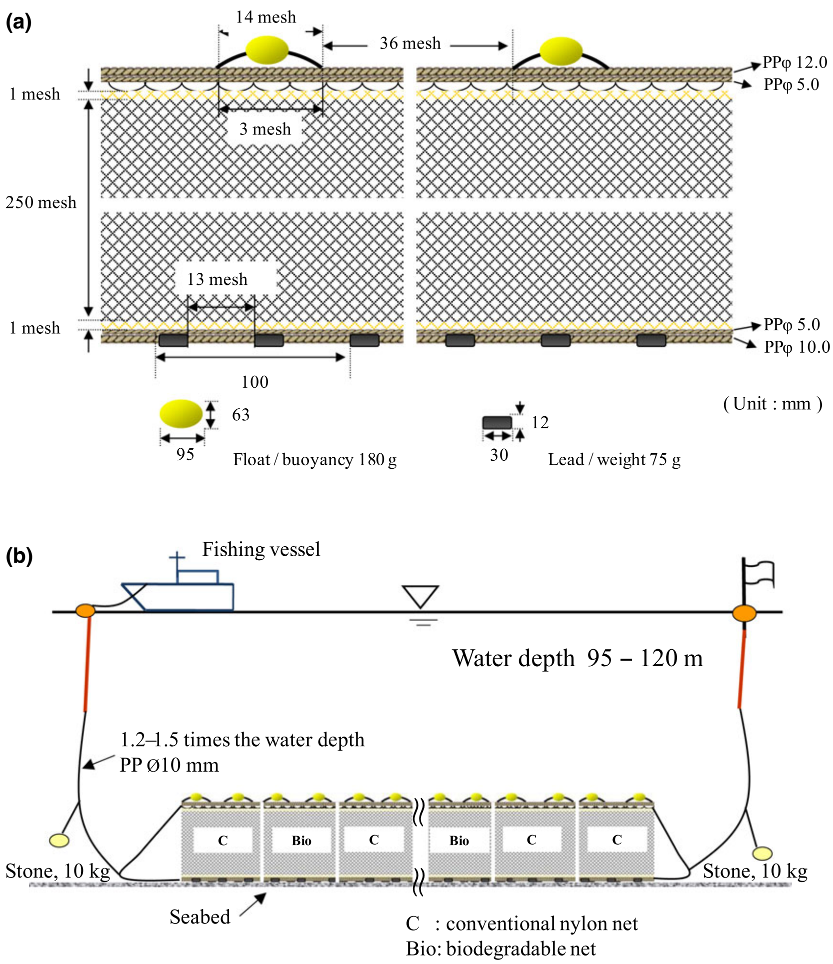

Figure 2 A schematic presentation of (a) the construction of the experimental driftnet for yellow croaker and (b) the layout of netting panels in the experimental fishing.

polypropylene (PP) ropes of ∅12 mm and ∅5 mm with floats (95 mm length, 63 mm outer diameter, buoyancy 180 g) installed every 36 meshes along the line. The lead line was 28.5-m long and consisted of two PP ropes of ∅10 mm and ∅5 mm with lead sinkers (30 mm length, 12 mm outer diameter, weight 75 g) installed at 13-mesh intervals.

Seven panels of the biodegradable net and conventional nylon net were used in the fishing trials. All panels were joined together to form a single fleet, with alternating biodegradable and conventional panels (Fig. 2b).

Sea trials for measuring fishing performance

The fishing trials were carried out in the southwestern coast of Korea with the help of a commercial yellow croaker fishing vessel 'Haechang' (GT 9.8 tons). The study site was near the Chooja-do and Jeju-do islands (Fig. 3).

The vessel left port before sunrise for the fishing trial operation, and nets were set as the vessel navigated in the same direction as the tidal current at a speed of 4–5 knots. Ten kg sinker stones were connected to the lead line to keep the equilibrium of the net during the drifting. The depth of the fishing ground was 95–120 m. The nets were hauled in after 5–6 h of soaking. Fish being caught in each net panel were counted by species, and their length and weight were measured. The fishing trial was carried out six times between 4 and 14 December 2014.

Degradation test of the biodegradable monofilament in seawater

In order to test the degradability of the biodegradable monofilament, monofilaments were spun at ∅0.30 mm. A total of 30 sets of experimental treatment biodegradable

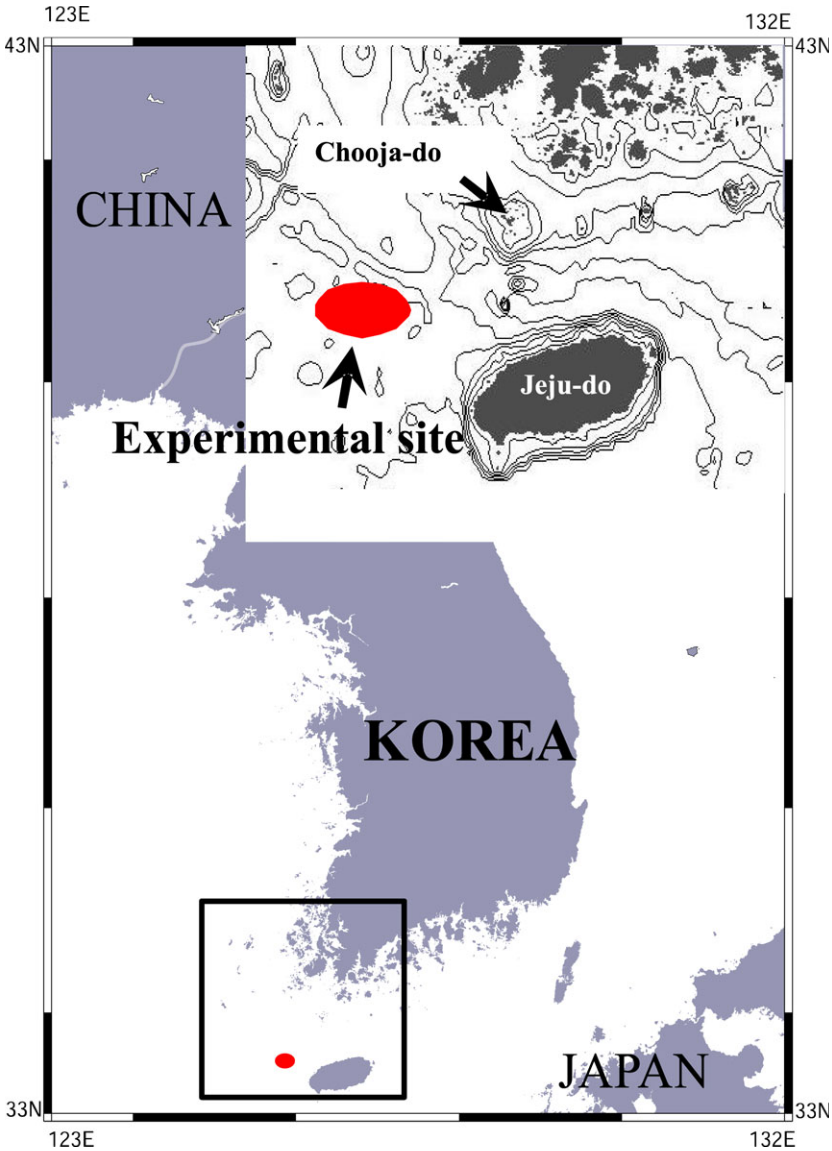

Figure 3 Location of the site of the fishing experiments.

monofilaments were prepared, where each set consisted of 10 monofilaments of 1 m in length. They were put into a square-based cube-shaped plastic case (700 × 700 × 250 mm, L × B × D) with sufficient water circulation which was immersed in the open sea. The samples were deployed in January 2010 near Kunsan-city to expose the test monofilaments to the marine environment rich in organic materials. The case containing the samples was anchored to the sea bed with water depth of 7 and 9 m during low and high tides respectively. The surface water temperature data obtained from an ocean observation buoy of the National Fisheries Research and Development Institute installed near the immersion spot were incorporated into the degradability analysis.

Samples were collected at 2-month intervals and the state of degradation of each sample was observed with a scanning electron microscope (SEM). All samples were subjected to chemical analysis, and one monofilament from each set of 10 monofilaments showing homogeneous degradation was selected for SEM observation.

Results

Twine property test

The breaking strength of the knotless nylon monofilament was 59.55 kg mm^{-2} when dry and 48.38 kg mm^{-2} when wet, an approximate decrease of 19% when wet (Table 1; Fig. 4). The elongation when dry and wet was 25.12% and 31.65%, respectively, demonstrating approximately a 25% increase when saturated with water.

The breaking strength of the knotless biodegradable monofilament was 47.74 kg mm^{-2} when dry and 47.10 kg mm^{-2} when wet (Table 1), indicating a similar strength as the conventional nylon monofilament when wet. The elongation of the knotless biodegradable monofilament in dry and wet conditions was only slightly different (24.32% and 24.59%), with the elongation when wet reaching about 77.7% of that of the nylon monofilament. There was no significant difference in the 95% confidence interval in terms of the breaking strength of conventional nylon and biodegradable knotless monofilaments during wet condition (*t*-test, $P = 0.08$, >0.05), although a significant difference was observed by the elongation (*t*-test, $P = 0.0001$, <0.05). The test results followed a normal distribution (Kolmogorov–Smirnov test, $P = 0.2$, >0.05).

The strength of the conventional knotted nylon monofilament was 43.92 kg mm^{-2} when dry and 39.11 kg mm^{-2} when wet, exhibiting an 11% decrease when wet (Table 2; Fig. 5). The elongation when dry and wet was 15.63% and 23.16%, respectively, demonstrating nearly a 1.5-fold increase (48%) when saturated with water.

The strength of the knotted biodegradable monofilament was 35.28 kg mm^{-2} when dry and 37.43 kg mm^{-2} when wet (Table 2), with the strength, when wet, reaching *c.* 95.7% of the strength of the nylon monofilament. The elongation when dry and wet did not show any noticeable difference (19.08% and 19.41% respectively) with the elongation, while wet reaching *c.* 83.8% of that of the nylon monofilament (Fig. 5).

Assuming that the test results follow a normal distribution (Kolmogorov–Smirnov test, $P = 0.2$, >0.05), there was no significant difference in the 95% confidence interval of the breaking strength of nylon and biodegradable knotted monofilaments during wet condition (*t*-test, $P = 0.116$, >0.05), although a significant difference was observed for elongation (*t*-test, $P = 0.0001$, <0.05).

Degradation of the biodegradable monofilament

During the 4-year test period (2010–2013), the lowest and highest surface water temperatures encountered near the experimental site were 0.4°C in January 2012 and 30.0°C in August 2013 (Fig. 6). Degradation rate was higher in summer months with higher water temperatures. On the basis of visual inspection done with a SEM, the degradation started *c.* 24 months after immersion in seawater (Fig. 7).

Netting twine stiffness test

In the stiffness tests, the average value of 10 measurements of the compressive load exerted on the conventional nylon monofilament at a predetermined resistance level decreased from 16.97 g in dry conditions to 10.80 g (63.6% of dry condition value) in wet conditions (Table 3). Twine flexibility increased by almost 1.6-fold in wet conditions. That is, a conventional nylon monofilament showed reduced stiffness and elevated flexibility when wet, while, in contrast, the biodegradable monofilament did not show any noticeable difference in stiffness when measured in dry and wet states (16.78 and 16.24 g respectively; Table 3). Moreover, the

Table 1 Strength and elongation of the knotless biodegradable and nylon monofilaments when dry and when wet

Material	Denier T_d	Weight g m^{-1}	Breaking strength Dry, kg mm^{-2}	Breaking strength Wet, kg mm^{-2}	Elongation Dry, %	Elongation Wet, %
Nylon monofilament Diameter: 0.29 mm	691.92	0.077 ± 0.0001	59.55 ± 1.12	48.38 ± 1.97	25.12 ± 1.61	31.65 ± 2.34
Biodegradable monofilament[a] Diameter: 0.30 mm	803.71	0.089 ± 0.0017	47.74 ± 0.70	47.10 ± 0.57	24.32 ± 0.52	24.59 ± 1.37

PBS, polybutylene succinate; PBAT, polybutylene adipate-co-terephthalate.
[a]PBS 82% + PBAT 18%.

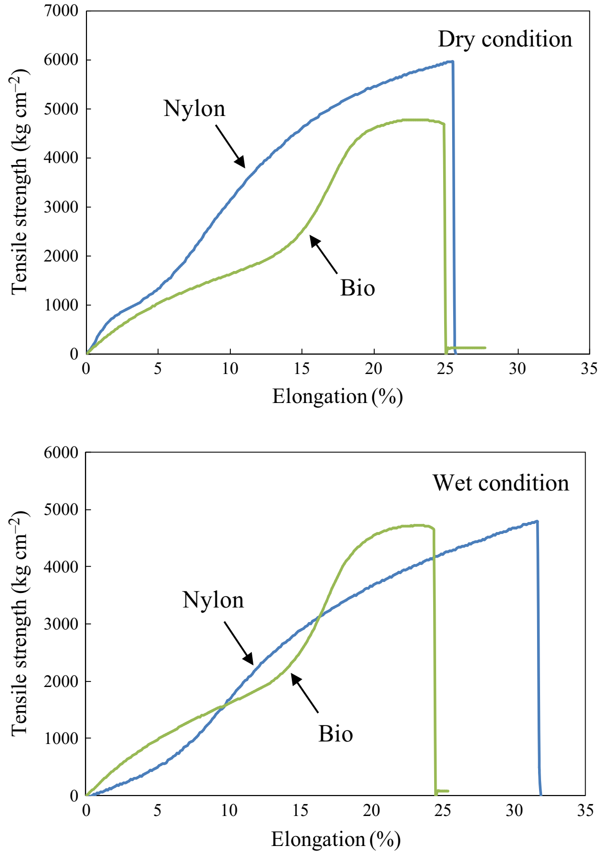

Figure 4 Pooled strength and elongation curves of knotless monofilament. Dry indicates that the specimens were dry and had not been immersed in water. Wet indicates the specimens were wet after having been immersed in distilled water for 24 h. 'Nylon' signifies nylon monofilament, 'bio' signifies biodegradable monofilament.

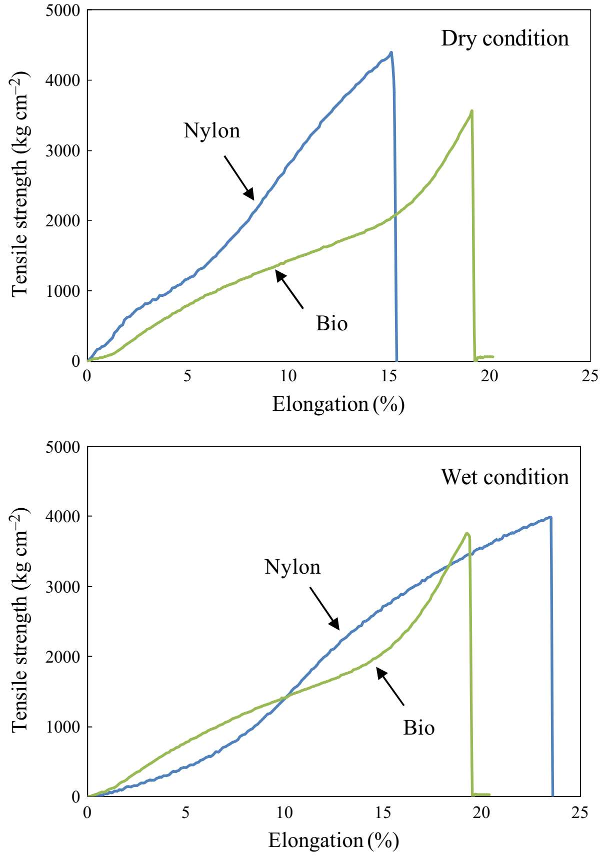

Figure 5 Pooled strength and elongation curves of knotted monofilament. For dry and wet conditions, see the caption in Figure 4.

stiffness value of the biodegradable monofilament while wet was 5.44 g higher than the stiffness value of wet nylon monofilament. This confirms that the nylon monofilament outperforms the biodegradable monofilament in flexibility while wet (Kolmogorov–Smirnov test, $P = 0.2$, >0.05; *t*-test, $P = 0.0001$, <0.05).

Fishing performance

The total number of yellow croaker caught in conventional nylon net panels was slightly higher than in biodegradable net panels (720 vs. 710 fish), as was also the case with the most important bycatch species, chub mackerel *Scomber japonicus* (414 vs. 379) (Table 4 and Fig. 8). There was a small difference in the overall weight of the total catch in the experimental versus control net panels (59.5 kg vs. 57.4 kg respectively). The total number of species caught by nylon and biodegradable nets during the fishing trials was 27 and 24 respectively (Table 5).

No significant difference in fishing performance was observed between the conventional and biodegradable nets (Kolmogorov–Smirnov test, $P = 0.2$, >0.05; *t*-test, $P = 0.914$, >0.05). However, a considerable difference was observed in the number of caught immature yellow croakers

Table 2 Strength and elongation of the knotted biodegradable and nylon monofilaments when dry and when wet

Material	Denier Td	Weight g m^{-1}	Breaking strength Dry, kg mm^{-2}	Breaking strength Wet, kg mm^{-2}	Elongation Dry, %	Elongation Wet, %
Nylon monofilament Diameter: 0.29 mm	691.92	0.077 ± 0.0001	43.92 ± 5.27	39.11 ± 4.51	15.63 ± 2.18	23.16 ± 4.22
Biodegradable monofilament[a] Diameter: 0.30 mm	803.71	0.089 ± 0.0017	35.28 ± 1.97	37.43 ± 1.29	19.08 ± 0.46	19.41 ± 0.34

PBS, polybutylene succinate; PBAT, polybutylene adipate-co-terephthalate.
[a]PBS 82% + PBAT 18%.

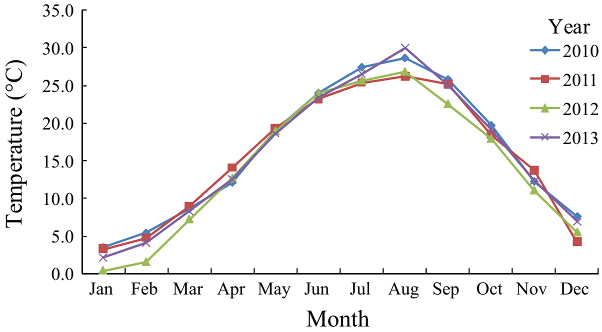

Figure 6 Surface seawater temperatures during 2010–2013 near the area of sample immersion.

Table 3 Stiffness of the nylon and biodegradable monofilaments when dry and when wet

Material	Nylon monofilament Mean ± SD	Biodegradable monofilament Mean ± SD
Condition		
Dry	16.97 ± 1.04	16.78 ± 1.31
Wet	10.80 ± 0.43	16.24 ± 0.86
d.f.	10	10
t-test	P = 0.0001, $P < 0.05$ indicates significance	

(length ≤ 19.6 cm, Kim *et al.*, 2009) between the conventional nylon nets and the biodegradable nets (16.5% vs. 11.1%, Fig. 8). Assuming that the catch rate of the immature yellow croaker follow a normal distribution (Kolmogorov–Smirnov test, P = 0.2, >0.05), there was a significant difference between nylon and biodegradable net catch rates of immature individuals (*t*-test, P = 0.036, <0.05).

Discussion

The biodegradable fishing nets used in this study began to degrade after about 2 years when immersed in seawater. By then a net made of this type of material would have lost a large part of its capacity to catch marine organisms, and most animals entangled in the net would likely be able to break the line and escape. Degradation rate was higher in higher water temperatures in summer, which indicate that the biodegradation process is temperature dependent. In fisheries that occur in cold water degradation would likely take a longer time relative to fisheries in warm tropical waters.

The critical question is how much faster a biodegradable net loses its ghost fishing capacity than a conventional nylon net, after being lost at sea. It is well demonstrated that although conventional nylon nets are highly resistant to degradation, they eventually lose their capability for ghost fishing, the time depending largely on conditions of the substrate on which the derelict gear is located, current strength, frequency of storm events and interactions with active fishing gear and vessels (e.g. Pawson, 2003; Santos *et al.*, 2003; Tschernij & Larsson, 2003; Nakashima & Matsuoka, 2004; Pham *et al.*, 2014). Hence, in case it takes about 2 years for a biodegradable net to decompose and lose the ghost fishing capability at sea, it may not give much advantage compared to a conventional nylon net. This is an area that certainly requires further studies. Experimental studies of biodegradation processes of biodegradable materials in seawater are still rather limited and with biodegradable fishing nets there is hardly any work done yet (but see Tabata & Kanehiro, 2004).

This study did not test the biodegradation of conventional nylon monofilaments. Previous studies have demonstrated that monofilament nylon nets may have a life time of several years or even decades when immersed in seawater (May, 1976; Carr *et al.*, 1990). Although the catching efficiency of

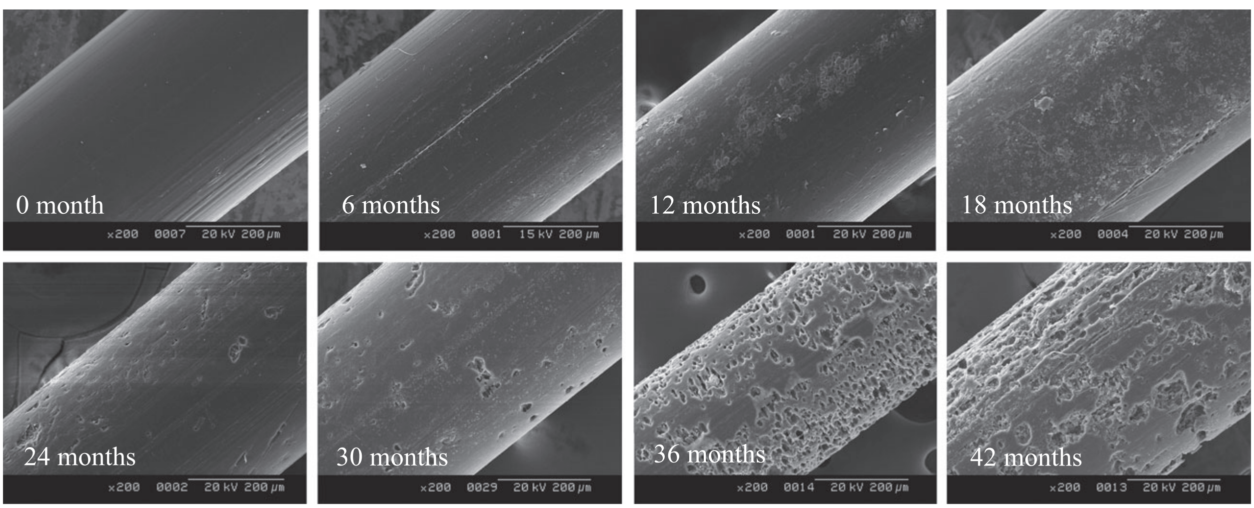

Figure 7 The degradation process of the immersed biodegradable monofilament observed with a scanning electron microscope. Pictures show the degradation states at 6-month intervals up to 42 months.

Table 4 Number of individuals and gross weight of each catch of the six fishing trials

Sea trials	Conventional nylon net: Number of catch	Conventional nylon net: Weight (g)	Biodegradable net: Number of catch	Biodegradable net: Weight (g)	Total: Number of catch	Total: Weight (g)
1	21	2144	30	2424	51	4568
2	86	7958	91	7975	177	15 933
3	214	16 789	208	16 220	422	33 009
4	195	15 461	190	15 531	385	30 992
5	79	7104	74	6158	153	13 262
6	125	10 044	117	9103	242	19 147
Total	720	59 500	710	57 411	1430	116 911

lost monofilament nets may dramatically decrease during the first weeks or months at sea, in certain conditions these nets may continue to catch some fish and other organisms over a long period of time (e.g. Humborstad *et al.*, 2003; Pawson, 2003; Revill & Dunlin, 2003).

It is worth of noting that the 'degradation test' did not use simulated derelict (ALDFG) gear, but instead put pieces of experimental biodegradable line in open seawater. This was a possible source of uncertainty because simulated derelict nets located at actual fishing grounds might experience different environmental conditions which could result in a different rate of degradation than observed in the current study.

Another issue is the end product of the degradation. Since biodegradable materials are finally degraded to carbon dioxide, methane and water, they do not have any additional impact on marine ecosystems once they have degraded (Tokiwa *et al.*, 2009; Kim *et al.*, 2014*b*,*c*). Nylon nets, on the contrary, may well lose their ghost fishing capacity when they degrade, but they do not disappear from the system. They may degrade into smaller plastic particles that may continue to disturb various processes in the marine ecosystem (Moore, 2008). This feature favors the use of biodegradable materials. In this context, it is worth of noting that a driftnet is composed not only of netting, but the gear also has a float line, lead line and floats that are frequently made of conventional synthetic materials. In this study the focus was only on the netting.

From the user point of view, the most important function of fishing gear is its fishing performance and cost-effectiveness. Therefore, to be accepted and adopted by the fishing sector, a new fishing gear should prove to be competitive compared with conventional fishing gear. Without adequate and proven fishing performance there is no possibility to persuade the potential users to take up a new material for their fishing gear.

The results of our material tests revealed that the biodegradable monofilament had slightly inferior physical properties compared to the conventional nylon monofilament. That would suggest a poorer fishing performance. Our sea trials, however, revealed that biodegradable nets captured almost as many (98.6%) yellow croakers as the conventional nets. A somewhat smaller number of the non-target species and juvenile fish were caught in the biodegradable nets compared to nylon nets. This difference may be because the highly flexible nylon nets easily catch fish which have spiny fins or gill covers, despite their size. In contrast, the twine of biodegradable nets had lower flexibility and therefore the net may not have as high capacity to catch certain type of species and sizes. It may allow small individuals to more easily pass through the meshes without being caught by their gills and spines. This may explain the lower catch rates of small individuals in biodegradable driftnets. Park *et al.* (2007*a*,*b*, 2010) reported similar findings in the catch efficiency of biodegradable nets for snow crab; fewer smaller crabs were caught in biodegradable nets compared to nylon nets. This may give some economic benefits because larger individuals often fetch a better price than smaller ones. Catching fewer small fish, however, does not necessarily mean the net has a higher catch rate of larger individuals, but that is a possibility. In any case, there is less work in cleaning the nets.

An important and highly desirable property of a fishing net material is its durability because it largely describes the service life of a gear. In the commercial driftnet fishery for

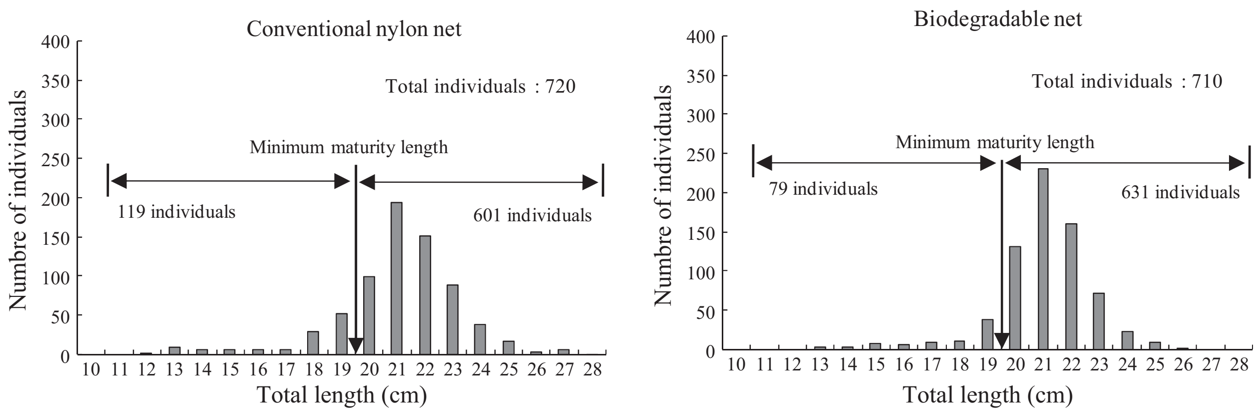

Figure 8 Length distributions of yellow croakers caught in conventional nylon net and biodegradable net.

Table 5 Species caught during the trial fishing period

		Conventional nylon net		Biodegradable net		Total	
Species	Scientific name	Number of catch	Weight (g)	Number of catch	Weight (g)	Number of catch	Weight (g)
Yellow croaker	*Larimichthys polyactis*	720	59 500	710	57 411	1430	116 911
Chub mackerel	*Scomber japonicus*	414	106 940	379	98 928	793	205 868
Largehead hairtail	*Trichiurus lepturus*	118	27 450	94	21 214	212	48 664
Searobin gurnard	*Chelidonichthys spinosus*	37	3357	26	2428	63	5785
Silver croaker	*Pennahia argentata*	21	2463	10	1120	31	3583
Bullet tuna	*Auxis rochei*	12	3998	8	2379	20	6377
Japanese barracuda	*Sphyraena japonica*	9	2326	15	3966	24	6292
Red-banded lobster	*Metanephrops thomsoni*	8	186	1	27	9	213
Brown croaker	*Miichthys miiuy*	7	3434	10	4151	17	7585
Daggertooth pike conger	*Muraenesox cinereus*	4	2007	2	1080	6	3087
Indian flathead	*Platycephalus indicus*	4	754	2	437	6	1191
Blotched eelpout	*Zoarces gillii*	4	337	1	84	5	421
Blackthroat seaperch	*Doederleinia berycoides*	3	384	4	666	7	1050
White flower croaker	*Nibea albiflora*	2	182	3	322	5	504
Armorclad rockfish	*Sebastes hubbsi*	2	88	3	163	5	251
Japanese jack mackerel	*Trachurus japonicus*	2	127	3	144	5	271
Japanese Spanish mackerel	*Scomberomorus niphonius*	2	1220	1	473	3	1693
Japanese flying squid	*Todarodes pacificus*	2	367	1	247	3	614
John dory	*Zeus faber*	1	516	1	751	2	1267
Mirror dory	*Zenopsis nebulosa*	1	174			1	174
Conger eel	*Conger myriaster*	1	824			1	824
Butterfish	*Psenopsis anomala*	1	119			1	119
Red seabream	*Pagrus major*	1	50	1	80	2	130
Cloudy catshark	*Scyliorhinus torazame*	1	188	1	188		
Brushtooth lizardfish	*Saurida undosquamis*	1	413	2	955	3	1368
Red tongue sole	*Cynoglossus joynerl*	1	45	1	45		
Yellow goosefish	*Lophius litulon*	1	289	1	239	2	528
Skipjack tuna	*Katsuwonus pelamis*			3	4892	3	4892
Bluespotted stargazer	*Xenocephalus elongatus*			1	75	1	75
Total		1380	217 738	1282	202 232	2662	419 970

yellow croaker, the conventional nylon net has an average service life of 3–12 months, depending largely on fishing ground conditions. If a biodegradable net has a shorter life span, it may not be an attractive alternative for the commercial fishery.

An additional feature of biodegradable materials is that they tend to be more expensive to produce than the conventional synthetic materials. A higher price of a net would not encourage a fisher to purchase it unless the net offers some other economic benefits that offset the high purchase price. Adoption of biodegradable fishing nets will likely have to be supported by some sort of subsidies.

Biodegradable materials have a wide variety of application in our daily lives. Their raw materials vary according to their application, and not all biodegradable resins can be used for fisheries. Some biodegradable resins rapidly biodegrade, such as surgical sutures, but they have low strength and elongation and are not suitable as materials for fishing net twines. Others, such as starch resins, are easily degradable in a dry state, but not in marine environments. Therefore, for the use as fishing net twines, there is only a narrow range of choices among biodegradable resins. Furthermore, considering the time lag from fabrication to circulation, fishing nets with high biodegradability capacity can begin to degrade even before their first use. These factors should be taken into account comprehensively when choosing biodegradable monofilaments for fishing gears. It is worth of noting that biodegradable materials can be used in many types of fishing gears and devices, and many useful applications may be found in the future.

In conclusion, our study suggests that the use of the biodegradable nets can at least in certain conditions contribute to a reduction in ghost fishing and may also reduce the capture of immature fish. Biodegradable nets may also contribute in the overall reduction of marine debris produced by fisheries. Nonetheless, there are still many uncertainties, challenges and knowledge gaps that have to be solved before we are able to draw firm conclusions about the overall benefits of these materials in various types of net fisheries. Finally, to reduce ghost fishing the primary goal has to be to prevent the loss of fishing gear in the first place. Education and training programs for fishermen would be valuable for raising the awareness of the impacts of ALDFG.

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